SOIL FERTILITY REGENERATION THROUGH IMPROVED FALLOW SYSTEMS IN SOUTHERN MALI

By

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Sub-Saharan Africa is perhaps the only major geographical region where famine and malnutrition still prevail and cause serious threat to humans. Socioeconomic and technical factors, including inadequate policies, economic backwardness, and alarming soil fertility decline, are believed to be the main causes for such threat.

Agroforestry technologies using leguminous shrubs and trees are reported to be effective in maintaining soil fertility through addition and cycling of nutrients, organic matter build up, and improvement of soil physical and chemical conditions. One such technology that has gained increased popularity in semiarid Africa is "improved fallows."

The research presented here has the overall objective of examining the relevance of improved fallow technology as a land-management option for soil fertility improvement in southern Mali. In a series of on-farm and on-station experiments, we examined the technical aspects of the potential of three perennial species [*Gliricidia sepium* (Jacq.) Walp. (gliricidia), *Pterocarpus erinaceus* Poir.(pterocarpus) and *Stylosanthes hamata* (L.) Taub. (stylosanthes)] for their suitability in improved fallows and soil fertility replenishment in the Koutiala region of southern Mali. Additionally, a linear programing model was used to assess the potential implications the adoption of such technology would have on the allocation of limited resources and on the end-of-year income of potential "early-adopter" households.

The findings indicated that although each species had some desirable characteristics for fallow improvement, none of them, taken alone, would be a perfect candidate for soil fertility replenishment in the region. The best opportunity may reside in a combination of species, especially gliricidia and stylosanthes. The application of the tree biomass to the soil during land preparation for sowing the crop resulted in satisfactory crop grain yields. Treatments receiving biomass of gliricidia + stylosanthes in mixture

(in on-farm trials) and gliricidia and stylosanthes alone (in the on-station experiment) yielded more maize grain than the region's 1998 average yield of 2020 kg ha^{-1}. However, considering the short-term nature of the experiments (two-year fallow duration), the results of the different soil tests (pH, N, available P, K, Ca, Mg, O.M., and CEC) were not conclusive in detecting any significant soil changes.

The gliricidia + stylosanthes improved fallows would only be of interest to for households using animal traction, which account for nearly 90% of the region's population, if they produce benefits other than improved grain yields such as fodder.

CHAPTER 1
GENERAL INTRODUCTION

Soil fertility decline is a major limiting factor for agricultural production and economic growth in sub-Saharan Africa (SSA). Inadequate land management and unfavorable price ratios between food crops and fertilizers are important elements in the spiral of land degradation occurring in this region, resulting in soil nutrient depletion and declining crop productivity (Breman, 1987; Pieri, 1992; Smaling, 1993; Breman and Kessler, 1995; Smaling and Braun, 1996; Sanchez et al., 1997; FAO, 1999a). The consumption of mineral fertilizers in SSA increased slowly by 0.6% during the last 10 years, compared to 4.4% in the other developing regions (FAO, 1999a). The total annual nutrient depletion in SSA is equivalent to 7.9 Mg yr^{-1} of N, P, and K, six times the amount of annual fertilizer consumption in the region (Sanchez et al., 1997). In the particular case of southern Mali, N-K-Mg budgets in 1992 were estimated to be -25, -20, and -5 kg per hectare per year indicating that as much as 40 to 60% of the income generated by farming in this region was based on "soil mining" (van der Pol, 1992). Calculations from

recent FAO statistics show that on average cotton production in Mali has increased 163% from 1993 to 1998. That this sharp increase is mainly due to soil mining is obvious, because during the same period the harvested area increased 187% while the average yields declined 13% below the 1980 figures (FAO, 1999b). This situation of alarming soil fertility decline puts at risk the sustainability of the production systems in SSA.

In the SSA region, farmers prefer to use fertilizers for production of cotton (*Gossypium hirsutum*) and other cash crops rather than food crops (cereals) because of the favorable credit facilities for cash crops and the very low prices of the food crops. Nevertheless, food crops occupy nearly 80% of the total arable land area. The very popular and age-old practice of shifting cultivation is no longer viable in the present farming systems characterized by high population growth rates (2.9%) (Cleaver and Schreider, 1994), and consequent increases in demand for food, fuel and shelter, lead to a drastic increase of land-use pressure. This situation has led to a shortening of the fallow period and its total elimination in many cases, accelerated soil erosion, and decrease in yields of basic food crops (Nair, 1993).

Good crop-residue management is beneficial for SSA agriculture. When applied as mulch, crop residues reduce soil erosion by protecting the soil against the impact of falling rain drops, trapping fine airborne soil particles that originated from remote areas, and enhancing the water-holding capacity of soils through the reduction of excessive evaporation. When incorporated in the soil, they contribute positively to nutrient cycling through the release of nutrients following decomposition. Unfortunately, crop residues have competing uses (fuel, construction, fodder). Sometimes they are simply burned during land preparation at the onset of the rainy season, often because of the lack of appropriate means to incorporate them, which exacerbates the negative nutrient balances. Using an average harvest index of 30% and a total millet straw of about 20 million tons for West Africa, Bationo and Mokwunye (1991) reported that an estimated total of over 65 million tons of N, P, and K would be removed from the millet-producing soils of SSA each year.

Traditionally, farmers use manure and other domestic wastes to improve soil fertility. Unfortunately, because of the practice of free-grazing of cattle and the poor integration of agriculture and livestock, the quantity of manure produced and applied is not sufficient to maintain

adequate soil fertility and meaningful crop yields (Batiano and Mokwunye, 1991).

It has become a priority to find other ways to maintain, if not improve, food crop yields for the resource-poor farmers who cannot afford to buy inorganic fertilizers. Because of inadequate production of locally available soil-improving materials (manure, compost, household waste, tree biomass, rock phosphate) and the high cost of chemical fertilizers, it is now being recognized that an integrated approach, combining the two sources of soil nutrients would be the most appropriate and effective way to tackle the soil fertility decline problem in SSA (Bekunda et al., 1997; Buresh et al., 1997; Giller et al., 1997; Palm et al., 1997; Sanchez et al., 1997; Phiri et al., 1999).

There is a general agreement that the use of compatible and desirable woody perennial species in arable land use systems can improve soil fertility (Sanchez, 1995). Nair (1993) mentioned four main means by which agroforestry systems could enhance soil fertility, namely (1) increase in soil organic matter content, (2) efficient nutrient cycling, (3) biological nitrogen fixation in the case of leguminous shrubs and woody perennials, and (4) possible complementarity interactions among associated species. Although these hypotheses are widely accepted by

scientists, there are situations where it is difficult for soil-improving trees to be integrated into the prevailing farming systems without fundamental changes, particularly in land tenure and resource-management practices.

Many studies have been conducted on fallow regeneration using woody species (Kwesiga and Coe, 1994; Buresh and Cooper, 1999) or perennial herbaceous species (Tarawali, 1991; DRSPR, 1992; CIPEA, 1992) alone, but tangible results are scarce for the specific case of Mali. Improved fallows that combine nitrogen-fixing woody and herbaceous species have the potential to mitigate to some extent the problem of soil fertility decline through production and effective management of large quantities of high-quality biomass. Although agroforestry species have been shown to have high potentials for soil fertility regeneration during short fallow periods of three to four years, examples of successful integration of this technology in sub-Saharan Western Africa are scarce. Furthermore, although it is hypothesized that a combination of woody and perennial herbaceous species would have greater potentials for fallow regeneration, the evidence is still not fully satisfactory. For example, very little is known about the species behavior in terms of shade tolerance and competition for light and nutrients when grown in association. In addition to these biophysical

constraints to technology generation, many social and economic constraints are mentioned as reasons for low adoption rates. These include insecure land-tenure systems, protection of the improved fallow against cattle, lack of proper land resource-management practices (Hoefsloot et al., 1993), and limited availability of agricultural lands.

It is with this background that the present study was undertaken to assess the potential of improved fallows for soil fertility replenishment and adapted implementation strategies of the technology in the farming systems of southern Mali. We hypothesize that (1) the association of fast-growing woody and herbaceous species provides soil protection and contributes to nutrient recycling, resulting in overall soil productivity enhancement in a relatively short period of time (3 to 4 years) compared with the traditional natural fallows; (2) the incorporation of imported biomass would improve soil fertility at least to the same extent as multipurpose trees (MPTs) would when they are grown and their biomass incorporated *in situ*; and (3) if means can be found to incorporate meaningful farmer evaluation of the treatments, their criteria may well be different from those stated above.

The main objectives of this research are (1) to identify the most suitable woody and herbaceous species

(from among a few selected species) for an agroforestry system and determine how they contribute, solely and in association, to soil fertility improvement through short-term fallows in southern Mali; (2) to assess the effectiveness of the incorporation of imported high-quality biomass compared to *in situ* application on soil fertility improvement; and (3)to modify the potentially promising treatments (following initial evaluations) to meet the criteria farmers use to assess soil-improving technologies.

The research was conducted in two supporting experiments. One, on-farm, in which the biomass of three selected agroforestry species was incorporated *in situ* after three years of their growth, and the other, on-station, where known quantities of biomass of the same species were collected from *ex situ* stands and applied to plots that had been under grass fallow for three years. Maize was the test crop. Soil properties and crop performance were monitored to assess the impact of the species in terms of soil fertility regeneration. Surveys were conducted to assess the farmers' perspectives and criteria for improved soil fertility. Linear programming was used to simulate the different changes likely to occur in average households with the introduction of the improved fallow technology.

The present study is presented in seven chapters. Following this introductory chapter (Chapter 1), Chapter 2 presents the potentials of traditional and newly developed tree-based land-use systems to soil fertility management and crop production in SSA. This chapter also examines the use of linear programing as a tool in support of decision making and policy formulation in agricultural development. The results of the on-farm trial which evaluates the adaptation of the species to the local environment and the impact of *in situ* application of their biomass on soil properties and maize grain yield are presented in Chapter 3. Chapter 4 is based on an experiment conducted on station and describes the rates of decomposition and release of N of *ex situ* applied biomass, N uptake by maize, and the overall impact on soil properties and crop yields. The evolution of soil organic matter fractions and the impact of nitrogen from the finer particle sizes on crop N nutrition and grain yield are presented in Chapter 5. A linear programing model is used to simulate the potential for the adoption of improved fallows, the likely changes in the allocation of resources, and the impact on family income for different-type households in the Koutiala region. The results are presented in Chapter 6. Finally, Chapter 7 presents a synthesis of the findings and general recommendations.

CHAPTER 2
LITERATURE REVIEW

Introduction

Farmers of semiarid sub-Saharan Africa are known for their ingenuity in all aspects of life, including their farming practices. When it comes to soil fertility management, they use traditional methods such as domestic wastes, farm-yard manure, crop rotations, and the incorporation of trees on farm lands. Such traditional farming systems, based on low external input, may even be qualified as highly intensive in terms of labor and other available resources. The decline in soil fertility referred to earlier is perhaps a result of not only climatic constraints but also an array of social factors. These include unfavorable markets, inappropriate government policies, and low transfer of technology, which jointly have resulted in the breakdown of traditional farming systems, rendering them inadequate to cope with the changed conditions of high population. Thus, soil-fertility depletion is a very complex problem, and it is unrealistic

to consider it in isolation from the many social and economic constraints that people face daily in the region.

The major land-use types of the region are (i) agricultural lands with scattered trees and short and long fallows originating from shifting cultivation, (ii) range lands, and (iii) forests. These are practiced in three major types of land-use systems: (i) shifting cultivation, (ii) parkland, and (iii) fallow land-use systems. The essential features of these three systems and the use of linear programing as decision making support are examined in the next section.

Traditional Tree-based Land-use Systems of Semiarid SSA

Slash-and-Burn/Shifting Cultivation

System description

Slash-and-burn or shifting cultivation refers to the land-management practice where a period of cropping (cropping phase) is alternated with a period in which the soil is rested without cropping (fallow phase). In general, the resting period is longer than the cropping period. This method of cultivation is often considered primitive, wasteful, and unproductive, since the areas in the world where it is practiced are precisely those associated with

low agricultural outputs and low yields per unit area of land (FAO, 1985). The system that is very common in the tropical developing countries of Africa, Latin America, and Southeast Asia, and appears in a variety of forms, depending on the local climatic, cultural, and economic conditions, is reported to still be the mainstay of traditional farming systems over vast areas of the tropics and subtropics (Nair, 1993).

The system consists of cutting woody species in a forested area to make land available for a short period (two to three years) for food crop production, followed by 15 to 20 years of bush fallow. Usually rudimentary, simple hand tools (e.g., axes, knives, hoes) are used for land clearing and farming. After the land is cleared of vegetation, part of the wood products are used as construction poles or fuel wood, and the debris is stacked in scattered piles and later burned in the cleared area.

In the savannas of West Africa vegetation, consisting primarily of grasses and some scattered trees and bushes, is cleared and burned in the dry season preceding the cultivation phase (Nair, 1993). This system results in a more thorough working of the soil for cropping, longer cropping periods, more severe weed infestation, and higher soil-erosion hazards after clearing and burning than in traditional shifting cultivation practices in the humid

tropics. In the special case of semiarid SSA, some important tree species are left uncut in the slash-and-burn process on the farm for fruit and/or fodder production, which would result in the formation of the so-called parkland systems.

Land use/management in any given region is but a reflection of the sociocultural and economic factors of the farming systems (Adedipe, 1984; Nair, 1993). In semiarid SSA, the change of the social fabric has led to smaller families and consequently to the fragmentation of land into smaller holdings. Cultivation has become more permanent with newer and more crop varieties, yet with low input. Over the years, the fallows became greatly reduced both in area and duration, putting in jeopardy the return of significant vegetative cover for the build-up of soil fertility.

In a study on the dynamics of regeneration and contribution of the vegetative cover to soil fertility replenishment in the Sudanian zone of Mali, Yossi et al. (1996) compared different land-clearing methods (with and without the removal of rootstocks and burning) in a shifting cultivation system. They monitored the evolution of postcultural vegetation and changes in soil properties and reported that the contribution of the vegetative cover after traditional fallows on soil fertility replenishment

was very little, especially if land clearance involved removal of rootstocks and burning. Unfortunately, the practice of rootstock removal is common in mechanized agriculture with cash crops such as cotton and peanut *(Arachis hypogaea)*. Similar results are reported from Senegal (Kaire, 1996) and Burkina Faso (Serpantie, 1996).

It is now widely accepted that the traditional practice of shifting cultivation is neither practical nor feasible in the prevailing farming systems because of socioeconomic, technical, and legal (land-tenure rights) constraints. Where natural fallows still exist, they are of very short duration (3 to 5 years). The decline in length of fallows on the one hand and the realization of the benefits of trees and shrubs in the fallow phase to restoration of soil fertility on the other have led to the concept of improved fallows, which is now a major area of research.

Soil fertility dynamics

The potential of the traditional shifting cultivation system for soil fertility regeneration through bush fallows has attracted much attention from the scientific community. Even in the 1950s and 1960s, scientific publications (e.g., Nye, 1958; Nye and Greenland, 1960) acknowledged the

beneficial effects of the system under low population densities, i.e., where the land-use factor is more than 10.

Clearing and burning, and the farm operations carried out during the cultivation phase, change both soil properties and the general environment. Clearing and burning cause (i) loss of most of the N, S, and C contained in the vegetation; (ii) destruction of litter and some of the soil organic matter; (iii) adverse effects on some physical and textural characteristics of the soil, in cases where wood is burned in thick piles, as in the "chitemene" system of central Africa (Matthews et al., 1992); and (iv) destruction of part of the microflora (Sanchez, 1976; Okigbo, 1984). When cultivation becomes more frequent, various changes take place, including (i) multiplication of pests and diseases, (ii) increased weed growth, (iii) erosion of topsoil, (iv) deterioration of the physical conditions of the soil, and (v) deterioration in the nutrient status of the soil and changes in the number and composition of soil organisms (Okigbo, 1984). These changes force farmers to abandon the land and move to other land.

Following clearing and burning, all soil nutrients other than N and S (which are lost through volatilization) are made more easily available to the crops (Sanchez, 1976) directly from ashes and through enhanced decomposition of the remaining, partially burned plant materials. This

enhanced crop nutrition is able to sustain subsistence crop production for a short term. During sufficiently long fallow periods, important vegetative regrowth is stimulated, especially in the Sudanian zones of the region, the soil tends to be rejuvenated, approaching the conditions of undisturbed soil under adequate vegetative cover where soil microorganisms and fauna are active in decomposition, mineral cycling, and the maintenance of favorable soil structure and texture. However, the soil fertility that is gradually built up during the fallow phase is disturbed abruptly by land clearing, and yields of crops raised following clearing decline sharply after two to three years of cultivation. Weeds become difficult to control and pest populations increase, leading to the abandonment of the farm to fallow.

The biophysical mechanisms and principles involved in soil fertility depletion and/or replenishment in these systems are still the same as identified four decades ago (Nye and Greenland, 1960). Most subsequent studies and reviews (Sanchez, 1976; Okigbo, 1984; Buresh and Tian, 1997; Rao et al., 1998) have only confirmed these processes and extended them to the other tree-based land-use systems. Basically, soil fertility depletion occurs mostly during the cropping phase through (i) accelerated mineralization of soil organic matter and organic inputs, (ii) loss of N

and S through volatilization, (iii) loss of nutrients through leaching, erosion, and crop harvests, and (iv) degradation of soil physical and chemical properties, leading to active soil erosion. Processes that lead to increased nutrient supply include (i) uptake of nutrients, especially nitrate N, from deeper soil layers, (ii) lateral capture of soil nutrients, (iii) biological N_2 fixation, and (iv) input of organic materials. It can be summarized that the main mechanisms regulating soil fertility status during the fallow phase are (1) increased nutrient supply, (2) increased nutrient availability, and (3) improved soil properties. Ways of manipulating these mechanisms through management practices will be examined briefly.

The major function of fallows in soil fertility is to recycle and conserve nutrients rather than to cause net increase in ecosystem nutrient stocks. In many respects, the recycling and conservation of nutrients are related to rates of biomass accumulation and nutrient immobilization in biomass. A potential exception to this is N. Although we generally assume that this is due to biological N fixation (BNF), there are virtually no examples where this has been conclusively demonstrated (Buresh and Cooper, 1999). In general, there is little change or net loss of nutrients during the first years of natural bush fallow. Losses of about 500 kg, 8 kg, and 140 to 590 kg ha^{-1} yr^{-1} of N, P, and

Ca, respectively, on newly established fallows and net increases in nutrient stocks in older ones have been reported from the humid tropics (Szott et al., 1999).

The many sociocultural, economic, and ecological changes experienced in the region have resulted in a breakdown of the traditional slash-and-burn system. Shifting cultivation as performed now in the region, because of the practice of burning, removal of rootstocks, overgrazing, and the shortened fallow period, makes a very limited contribution to nutrient cycling. In regions where short-duration natural fallows still exist, regeneration of the vegetative cover consists of annual and/or semi-perennial grasses, mostly of the genera *Andropogon*, *Borreria*, *Cenchrus*, *Digitaria*, and *Pennisetum*. These species, contrary to shrubs and trees, have relatively shallow rooting depths and therefore may be less efficient in recycling nutrients from deeper soil horizons.

Shrub and grass species in traditional bush fallows may produce large quantities of dry matter at the expense of the already nutrient-depleted soils. However, this biomass is of poor quality (high C:N ratios) and is annually removed through grazing and uncontrolled wildfires during the dry season. Bush fallows are also the main source for fuelwood, medicinal products, and small timber

for construction, the increasing demand for which further hampers vegetative growth. Thus, the basic avenues through which bush fallows might contribute positively to making nutrients more available, i.e., improvement of soil organic matter content, litter fall and decomposition/mineralization, are limited. The capture and deposition of nutrients from wind-blown dusts, though plausible because of the occurrence of wind erosion, is poorly documented for the region and is supposed to be of minor importance. They may contribute more to nutrient depletion and transfer of fertility through overexploitation of the aboveground biomass than making nutrients more available.

In the region, continuous farming of the deeper soils in valley bottoms is common because they offer a higher return on investments; thus, fallowing is only practiced on marginal lands. The very nature of these soils (low base status), the management of bush fallows (overgrazing, fires, and fuel wood gathering), and the drastic reduction of the length of the fallow period favor the destruction of the soil physical and chemical properties leading to accelerated soil erosion. Detachment and displacement of finer soil particles exacerbate the negative soil nutrient status.

In summary, there is sufficient scientific evidence to suggest that although the traditional slash-and-burn system is no longer sustainable, the mechanisms of soil improvement by trees that is a key principle of the system could be exploited to design more sustainable technologies.

The Parkland System

System description

The parkland system is the most widespread indigenous agroforestry system in the arid and semiarid lowlands of SSA. The system originated from the old practice of shifting cultivation. While clearing the forest for agricultural production, farmers conserve trees that grow on crop fields to protect crops and workers from the sun and to supply fuelwood, fodder, fruits, and medicinal products (Kater et al., 1992; Kessler, 1992; Jaiyeoba, 1996). In the Sahel zone, woody species producing useful products and providing shade are preferred; other trees are cut at knee height and burned with their branches. Some of the burned trees die, but many resprout every year (Breman and Kessler, 1995). Though natural regeneration of such species is favored and even assisted during the cropping phase, planting them is rather exceptional.

The trees that are maintained assiduously include a large number of species. The most common are *Acacia* spp., *Adansonia digitata, Bombax costatum, Borasus aethiopium, Faidherbia albida, Parkia biglobosa, Prosopia* spp., *Pterocarpus erinaceus,* and *Vitellaria paradoxa*. The species diversity in the parkland system is very much related to ecological conditions: as the rainfall in a region increases, the species diversity and system complexity increase (Nair, 1993). This is illustrated in the semiarid SSA region where parklands are of higher density and diversity in the Sudanian zones (900 to 1200 mm rainfall per year) than in the Sahelian ones (150 to 600 mm). Breman and Kessler (1995) report that the average densities range from 5 to 20 trees per ha. The highest densities recorded are 300 *Borassus aethiopium* per ha and 50 *Faidherbia albida* per ha.

Bonkoungou (1992) highlights that Sudano-Sahelian Africa has not developed a planting tradition; thus, today many tree stands are being degraded by the combined effects of land pressure and drought. The absence of planting tradition constitutes, at least in part, a serious constraint to regenerating existing parks or establishing new ones. A general observation is that the parklands are victim of ageing (the trees are decades or even hundreds of

years old). Trees and shrubs are either dying or very unproductive both in terms of biomass, soil fertility improvement, and other products and services. The very low tree density (5 to 20 trees ha^{-1}) mentioned by Breman and Kessler (1992) as compared with the 20 to 50 trees ha^{-1} density about 30 years ago is striking evidence. Research and development efforts have been recently focused on (i) assisted natural regeneration of native species, where farmers protect stump sprouts and root suckers, (ii) experiments with different management practices (timing and severity of pruning), and (iii) planting young seedlings (including new species) in an effort to increase tree density and/or rejuvenate the system. However, these efforts are limited in scope and not yet well documented.

Soil fertility dynamics

Although researchers generally agree that trees do have a positive impact on soil fertility parameters, there is no unanimity of opinion on their overall value. For example, several authors have reported that trees in parklands impede crop growth (Ruthenberg, 1980; Kessler and Breman, 1991; Kater et al., 1992; Kessler, 1992; Wilson et al., 1998). Results from Mali (Kater et al., 1992) and Burkina Faso (Kessler, 1992) indicate crop yield declines of 60 and 70%, respectively, under tree crowns compared to

the open field. On the other hand, many other studies have shown that crop yields are higher, especially under *Faidherbia albida* than in the open field (Dancette and Poulin, 1969; Charreau, 1974; Poschen, 1986; CTFT, 1988), possibly because of improvement of the soil fertility. From a study conducted on *F. albida* parks at Watinoma, Burikana Faso, Depommier et al. (1992) reported higher concentration of soil organic matter, N, and exchangeable bases in soil beneath the tree crown than outside. Similarly, sorghum crop grain yields were up to 200% higher under the tree crown than in the control plot outside the crown. Kater et al. (1992) found higher average carbon concentration and higher available Mg and K under *P. biglobosa* and *V. paradoxa* tree canopies as compared to the open field in Mali, while Kessler (1992) found no significant differences at different locations from the trunk of the same tree species in Burkina Faso.

The parkland system, though not always associated with higher crop yields under the tree canopy, provides diverse products (forage, fruits, and small timber) and services (shelter and soil erosion control) and enjoys wide acceptance by the farmers. From their study on the interaction between *Parkia biglobosa* (*néré*) and sorghum in Burkina Faso, Wilson et al. (1998) concluded that the

farmers' current practice of sowing under the crowns of trees produced a worthwhile crop yield and that socially, economically, and ecologically the sorghum-*néré* parkland system was worth retaining.

The main mechanisms involved in soil fertility changes in parkland systems are similar to the ones highlighted for shifting cultivation, but the impact is generally localized in the area directly under the tree crown. Some scientists argue that the system favors a redistribution or concentration of soil nutrients under the trees at the expense of large areas in the open field leading to microsites of fertility (Breman and Kessler, 1995). In addition, there is a competition effect (Rao et al., 1998) which explains poor crop growth and yield decline under the tree crown. This competition between trees and the associated crop could be for soil and/or environmental factors. Kessler (1992) found in Burkina Faso that the photosynthetically active radiation (PAR) was reduced to as low as 20% of the open field under *néré* trees, leading to serious decline in crop yield. In the same region and in similar parklands, Wilson et al. (1998) reported that the mean photosynthetic photon flux density (PPFD) was reduced to 26% of full sun levels under the crown of *néré* trees, confirming Kessler's findings. Although competition for

nutrients and soil water might be expected, no major study in this area has reported such competitive effects, probably because of the deep rooting system and the advanced age of the major associated trees. However, strong scientific evidence on competition for limited soil nutrients and water exists in other simultaneous systems such as live fences, shelterbelts, and alley cropping (Singh et al., 1989; Ong et al., 1991; Govindarajan et al., 1996).

Three mechanisms have been put forward to explain the fairly well-known phenomenon of crop-yield increases under *Faidherbia albida* trees. First, the nutrient pump mechanism (CTFT, 1988): the fixed N_2 and assimilated soil nutrients are cycled to the soil surface through litter fall. The second mechanism, known as the albida effect (H. Breman, pers. com.; Jung, 1966), claims the effect on crop yield under this tree is mainly due to the concentration of nutrients (urine and defecation) from animals resting under the shade and browsing its falling leaves and fruits during the hot and dry season, and also from nesting birds. This is so because of the reverse phenology of the plant, i.e., losing leaves during the rainy season and growing actively during the dry one. The third mechanism is that the effect might well be due to preexisting favorable microsite

effects at locations where the tree grows (Charreau and Vidal, 1965; Dancette and Poulain, 1969; Geiger et al., 1994; Jaiyeoba, 1996). In reality, it could well be a combination of some or all of these mechanisms, and possibly some not-yet-determined ones.

The parkland system has potential to improve soil fertility through nutrient cycling, i.e., uptake of leached N from deeper soil layers, litter fall and decomposition, and root turnover. Some tree species have an extensive lateral root system (Groot and Soumaré, 1995). They may concentrate nutrients under their crown at the expense of large surface areas, which creates micro sites of varying fertility within the same farm. However, the effect is mostly confined to the area directly under the crown of the trees, and the impact on crop yield is variable.

Soil organic C concentration is reported to be higher under tree canopy than in the open area, which in conjunction with the microclimatic effects (lower radiant temperatures and wind speed, reduced soil erosion and evaporation of soil water) ameliorate the soil's physical properties (structure, aggregate stability, infiltration, water-holding capacity) and chemical characteristics (pH, CEC, N, P, K). However, these ameliorations are not always accompanied by corresponding increases in yield of crops grown beneath the trees.

The traditional parkland system faces three major constraints, which greatly reduce its contribution to nutrient cycling in the region. First, the parklands are the victim of ageing, as mentioned earlier. Second, parkland trees are indigenous species, the silviculture of which is poorly understood and little is known about their management as compared to the other multipurpose tree species (MPTs) such as *Calliandra calothyrsus*, *Gliricidia sepuim*, *Leucaena leucocepala*, and *Senna siamea* that have been preferentially studied in agroforestry. Moreover, their natural/assisted regeneration is difficult and hampered by wildfires and animals in search of pasture, particularly in the dry season. The third constraint is more legal than technical in nature. In many countries (Burkina Faso, Mali, Niger, and Senegal), as a legacy of the colonization and as a measure to protect/conserve important native species such as *Parkia biglobosa*, *Vitellaria paradoxa*, and *Faidherbia albiba*, many of the trees found on parklands are classified "totally protected species" by foresters, *de facto* excluding any intervention even by owner farmers. This conflict of interest between conservation and management has prevailed so long that the different parties (government officials and farmers) failed to find a common ground as far as management/tending is

concerned. These different constraints must be addressed appropriately if greater benefits are sought from the parkland system in region.

New Approaches to Tree-based Land-use Systems

Today, as the principles of soil improvement under vegetative cover are becoming better established, the reasons for soil degradation and fertility decline when forested lands are converted to other uses (permanent agriculture, pasture) are also better understood (Sanchez, 1976; Lal, 1989; Sharma, 1992; Nair, 1993). The challenge now is to make the best use of these principles in the design of appropriate technologies to cope with the problems. Because of the breakdown of the traditional shifting cultivation system and the disruption of its soil-fertility-improvement mechanisms, it has become necessary to adopt new technologies capable of optimizing nutrient cycling in permanent agricultural production systems. *Fodder banks* and *improved fallows* are two examples of such tree/shrub-based technologies that are gaining interest in the region.

Fodder Bank/Tree + Animal (+ Crop) Systems

System description

The system consists of planting (semi-) perennial herbaceous species on arable lands as short-duration fallows for providing better-quality fodder for enhancing livestock productivity and *inter alia* soil fertility improvement. The planted species are allowed to grow to optimum production of quality biomass, which generally corresponds with the flowering stage. Then, they are either grazed on site by cattle or cut, carried, and stocked for later use during the six-to-seven-month dry season when forage shortages are acute in the region. Often, the term "fodder bank" is used to designate such improved fallows mainly due to the emphasis on animal production in the system. This system was introduced in the early 1970s particularly by the International Livestock Research Institute (ILRI, formerly International Livestock Center for Africa, ILCA) and the *Office de Recherches Scientifiques et Technologiques d'Outre-Mer* (ORSTOM) for the entire region. Until very recently, species selection was based more on environmental and feed-quality criteria than on aspects of soil fertility improvement. So far, the most-used species include *Andropogon gayanus*, *Brachiaria*

ruziziensis, *Cajanus cajan*, *Cenchrus ciliaris*, *Centrosema pubescens*, *Crotalaria* spp., *Dolichos lablab*, *Stylosanthes hamata*, *Panicum maximum*, and *Vigna unguiculata*. Among these, *Stylosanthes hamata* is reported to be the most productive and suited to local conditions (DRSPR, 1992; Hoefsloot et al. 1993; Tarawali et al., 1997).

The technology has been challenged by three major constraints. First, the timing for cutting the biomass to ensure better feed quality: cutting at flowering stage coincides with increased demand for labor in the household for other activities. Also, experience shows that drying the fresh-cut biomass requires additional investments in building shelters to prevent it from rain damage. Second, in the case of species capable of producing high-quality human food, such as *Cajanus cajan* and *Vigna unguiculata*, most farmers would rather let them grow to maturity. This not only conflicts with the objective of providing high-quality fodder, but also reduces considerably the quantity of dry matter for "cut-and-carry." The third constraint is related to protection. In case of semi-perennials such as *Andropogon gayanus*, *Brachiaria ruziziensis*, *Cajanus cajan*, and *Stylosanthes* spp., the planted fodder banks tend to be the only source of green pasture soon after crop harvest and during the dry season. Thus, there is a strong pressure

from free-grazing cattle making protection necessary. Investments in protection (fences) makes the cost of the technology prohibitive in these low-income farming systems. Recently, because of these constraints and soil fertility decline, there has been a shift to using shrubs (*Acacia* spp., *Gliricidia sepium*, *Leucaena leucocephala*, *Pterocarpus* spp., *Sesbania sesban*, and so on) in addition to the already known and promoted herbaceous species of the early 1970s. However, the results in terms of adoption by farmers are site specific.

Potential for soil fertility replenishment

Although until very recently most of the research on fodder banks involved only herbaceous species, the fodder-bank technology has shown some evidence of soil-fertility-improvement potential. For example, the farming systems research team in southern Mali (DRSPR, now ESPGRN) introduced six perennial herbaceous species (*Brachiaria ruziziensis*, *Cenchrus ciliaris*, *Clitoria ternatea*, *Macroptilium atropurpureum*, *Panicum maximum*, and *Stylosanthes hamata*) as fallow cover crops to improve soil fertility in on-farm trials from 1988 to 1991. Once every year the biomass was cut, carried outside the plots and fed to cattle. After three years, all the remaining biomass was

incorporated in the soil during land preparation and sorghum (*Sorghum bicolor*) was planted. The study showed that *Stylosanthes hamata* produced a 1.9 to 2.3% increase in soil nitrogen compared to 0.8 to 1.7% for the non-leguminous species and 1 to 1.4% for the traditional grass fallow. These improvements were reflected in higher sorghum yields (DRSPR, 1992). From the same region, Diarra and de Leeuw (1994) reported a C:N ratio change of the topsoil from 25 to 12 indicating that the introduction of appropriate legume/forage species can achieve soil fertility improvements. In another study in Nigeria, Lal et al. (1979) used three grasses and five legumes in combination as a two-year fallow. They found gains of C (3900 kg/ha), N (580 kg/ha), and CEC (2.3 $cmol_c/kg$) in the fodder-bank plots over the control. However, the performance of the subsequent crop was not reported. In a *S. hamata/S. capitata* trial in the same region, Tarawali and Peters (1997) found that organic C, soil N, and subsequent maize yields were higher in the mixtures than in plots preceded by either sole *S. capitata* or *S. hamata* suggesting a complementarity effect in the case of mixtures.

The mechanisms involved in soil-fertility improvement here too are similar to the ones already highlighted in the

previous sections. Because fodder banks share many similarities with improved fallows, these mechanisms are discussed together with those for improved fallows in the following section.

The Improved Fallow Systems

System description

In improved fallow systems, a tree, shrub, or herbaceous species is grown in rotation with cultivated crops to achieve the soil fertility replenishment benefits of natural fallows within a shorter time. The ideal tree species is typically fast growing, N_2-fixing, and efficient in nutrient cycling (Jama et al., 1998). The aboveground biomass is regularly pruned to prevent the species from growing too large and becoming difficult to control during the cropping phase. Depending on the environmental conditions and the plant characteristics, some species may be pruned more than once during the growing season. Large branches and stems are generally used as small timber and/or fuel wood. The remaining leafy materials, i.e., leaves, twigs, and small branches are higher quality biomass which may be used in many different ways depending on the producers' objectives. Direct *in situ* application

of biomass into the soil at seed-bed preparation is the most common technique for soil fertility improvement in the humid regions. In the drier regions, feeding the biomass to cattle and applying the resulting farm-yard manure to the soil during seed-bed preparation is becoming more popular because it addresses both feed production and soil fertility constraints.

The system has gone through numerous changes dictated by the various constraints and is still evolving rapidly. All stakeholders in the agricultural sector (farmers, decision makers, researchers, and extension workers) have come to the conclusion that declining soil fertility and poor land resource management are the main factors hampering agricultural production and food security in the region. Thus, most programs are geared to improving soil fertility through the use of locally available materials for better nutrient management and cycling. Technical experts believe that the basic scientific principles of soil-fertility improvement using improved fallows are well understood (Buresh and Cooper, 1999), and that the main challenge is in the implementation of the technology at village/farm level taking into consideration the sociocultural and economic aspects through on-farm research trials.

Potentials for soil-fertility replenishment

Thanks to the numerous studies on the topic in tropical Africa (Rao et al., 1998; Buresh and Cooper, 1999) a substantial body of information is now available on the contribution of such improved fallows to soil physical and chemical properties (Kwesiga and Coe, 1994; Mugendi et al., 1994; Juo et al., 1995; Mafongoya, 1995; Mafongoya et al., 1997). Earlier findings from Nigeria supported the beneficial effects of improved fallow systems on soil physical and chemical properties (Juo et al., 1995) mainly through more organic matter build-up and increase in nitrate-N and K concentration in the soil (Adejuwon and Adesina, 1990). Mafongoya et al. (1997) studied the potential of prunings from three multipurpose woody species as sources of N to a maize crop in Zimbabwe. They concluded that application of biomass at planting gave the highest N uptake efficiency (NUE) due to better synchrony with maximum crop nutrient demand. They also found that incorporation of biomass gave higher NUE than when surface-applied as mulch due to better decomposition and N release. Mugendi et al. (1994) evaluated the potential of incorporated leaves of seven MPTs (*Calliandra calothyrsus*, *Gliricidia sepuim*, *Grevillia robusta*, *Leucaena leucocephala*, *Senna siamea*, *Senna spectabilis* and *Sesbania*

sesban) as source of N for maize in Kenya. They concluded that leaves of all tree species supplied reasonable quantities of N to a maize crop as evidenced by higher maize shoot dry weight and higher N concentration except *G. robusta*, which suppressed yield and the effects were more significant with higher rate of biomass application.

Drechsel et al. (1991) found higher soil pH, CEC, and exchangeable cations on planted fallows compared to natural fallows in Central Togo. They also reported that topsoil OM was enhanced by up to 60% over grass fallow. They hypothesized that the higher soil pH was due to the Ca-pumping effect of trees. However, they cautioned that integration of trees on crop lands might have negative impacts such as competition for limited soil water and nutrients, and decreases in soil nutrient reserves in case they were harvested and exported outside the system.

On the other hand, Schroth et al. (1995) reported from a combined field and laboratory study, involving nine tree species of which six were N_2-fixing, on a ferralitic Cambisol in Central Côte d'Ivoire that subsoil pH values were relatively lower for some N_2-fixing species. They attributed this to higher cation uptake, and emphasized the risk of increased nitrate and cation leaching associated with N_2 fixation. They also reported that averaged across

species 48.6% of the root-C and 52.9% of the root-N in the 0 to 60-cm were concentrated in the top 10 cm of soil. There was a correlation between root-C and N mineralization which could be due to the stabilizing effect of root on soil aggregates, thus physically protecting labile soil OM. The implication of their findings for fallow species selection is that N availability for subsequent crops could be increased by choosing fallow species with high litter production and high root mass. Several other studies have also reported the potential of high-quality biomass for supplying nutrients to agricultural crops in resource-poor farming systems through integration of MPTs, for example, as fallow improvement species (Mittal et al., 1992; Xu et al., 1993; Kwesiga and Coe, 1994; Harmand and Njiti, 1998; Jama et al., 1998; Louppe et al., 1998).

Mechanisms of Soil Fertility Replenishment

The main avenues through which trees, shrubs, and perennial herbaceous species can improve soil fertility have been well articulated by a number of authors (Nair, 1993; Kwesiga and Coe, 1994; Mugendi et al., 1994; Breman and Kessler, 1995; Juo et al., 1995; Mafongoya, 1995; Nair et al., 1995; Sanchez et al., 1997; Nair et al., 1999). They have recently been summarized by Buresh and Tian

(1998) as: (i) increased supply of nutrients through increased inputs and reduced outputs, (ii) increased availability of nutrients through enhanced nutrient cycling and conversion of nutrients to more labile forms, and (iii) a more favorable environment for plant growth through improved soil chemical and physical properties, i.e., nutrient cycling.

Nutrient cycling refers to the transfer of nutrients already in the soil-plant system (Sanchez and Palm, 1996; Nair et al., 1999). The process is mainly based on (i) the uptake of soil mineral elements, particularly nitrate, in deep soil layers by the roots of the perennials capable of exploiting a larger volume of soil (Buresh and Tian, 1997; Jama et al., 1998) and (ii) their redistribution in the surface layers through root slough and decay, litter fall and decomposition (Schroth, 1995), and the application of the prunings to the soil (Jama, 1993; Mafongoya, 1995; Byard et al., 1996; Mugendi and Nair, 1997).

Buresh and Tian (1998) detected subsoil nitrate levels in the order of 70 to 315 kg N ha^{-1} at 0.5- to 2-m depth in maize-based systems on Oxisols and Alfisols in western Kenya. The accumulation of nitrogen in deep soil layers is a result of leaching from the decomposing organic materials and applied inorganic N fertilizers because of inefficient crop uptake due to poor synchrony. Jama et al. (1998)

reported from a similar system in Kenya that *Calliandra calothyrsus* and *Sesbania sesban* reduced soil nitrate in the top 2 m by about 150 to 200 kg N ha^{-1} within 11 months after establishment and effectively captured subsoil nitrate; thus, fast-growing trees with deep rooting systems can rapidly reduce subsoil nitrate. Many other findings confirm this phenomenon which can be exploited in the design of agroforestry systems to enhance N cycling in low input farming systems (Noordwijk et al., 1991; Groot and Soumaré, 1995; Schroth, 1995; Schroth and Zech, 1995).

With respect to supply of nutrients, the function of fodder bank and improved fallow systems is mainly conservation of nutrients through accumulation and immobilization in biomass. Though the addition of N to the soil through BNF has not been conclusively demonstrated (Buresh and Cooper, 1999) and despite the predominance of low base status soils in the region, reports in the literature suggest that the contribution of N_2 fixation to ecosystem N stocks in these soils can be 100 kg ha^{-1} yr^{-1} (Giller and Wilson, 1991; Giller and Cardisch, 1995) and up to 300 kg ha^{-1} yr^{-1} on high base status soils (Sanginga et al., 1995; Giller et al., 1997).

Soil nutrients, whether recycled or added, may be more available for crop uptake in a favorable soil environment.

Fodder bank and improved fallow systems protect the soil against erosion and leaching of nutrients, and enhance its microbial activities which may trigger a number of beneficial soil chemical reactions. For example, Buresh et al. (1997) reported increases in microbial biomass P and light fraction soil OM P on *Sesbania sesban* fallows on an Eutrudox in Kenya, probably due to increased soil pH, CEC and micorrhizal activity.

Although MPTs contribute very little to soil phosphorus (Rao et al., 1998; Sanchez and Palm, 1996; Drechsel et al., 1991), they do have a great impact in making available the fixed soil P through solubilization. This avenue is of great importance in semiarid regions where the soils are slightly acidic and have high P-fixing capacity (Sanchez, 1976; Jones and Wild, 1975; Brady and Weil, 1999).

It is well documented that the nutrients added to an agroforestry system are less subject to losses caused by soil erosion, leaching, and/or volatilization because they are incorporated into active as well as less active pools of soil OM (Sanchez and Palm, 1996) thus making the system more sustainable.

The improved fallow systems are especially important because they offer greater opportunities for achieving the

objectives of long bush fallows in shorter time. The species are deliberately selected based on specific characteristics, i.e., adaptability to the local environment, growth characteristics, capacity to fix atmospheric N_2, resprouting after pruning, and quality of their biomass. They are known to contribute to improving soil OM status, and hence, soil chemical and physical properties better than fodder banks which are aimed more at improving livestock productivity. The latter practice may conflict with soil-fertility-replenishment objectives if sufficient manure is not returned to the farm. In addition, fodder bank systems may not have great potential for uptake of leached nutrients from lower soil layers, because the most widely used species are grasses and semi-perennial herbaceous legumes that may not have as deep a root system as that of fallow trees.

To conclude this section, tree-based approaches to soil fertility improvement and management have either proven themselves or indicated their potential in semiarid SSA. The basic biophysical mechanisms involved in the process and the evolution of the farming systems in the region indicate that the new approaches (fodder banks and improved fallows) have greater potential than the traditional ones that are seriously challenged by socioeconomic and institutional constraints. It is also

important in this context to focus on some main issues to be considered, both in the light of the existing scientific knowledge and from the rural farmers' perspective, if greater benefits are sought from the traditional and improved tree-based technologies for the regeneration of soil fertility.

Directions for the Future of Tree-Based Soil Fertility Improvement in Semiarid SSA

Some key future research areas which merit further understanding are highlighted for each system in the following section.

The Parkland System

In terms of improvement, the system has not benefitted enough from the immense scientific information available mainly because of our poor understanding of the sociocultural aspects of the system (Bonkoungou, 1992). More research should be directed to this area. In terms of management, our present scientific knowledge must be used more efficiently for designing strategies capable of expanding the microsite improvement effects without exacerbating the competition effects reported by numerous scientists. This may be achieved through better species selection, increased tree density, and introduction of

appropriate pruning techniques in on-farm trials. Ageing of existing trees has been recognized as one of the constraints limiting productivity of these systems. Systematic efforts involving a judicious combination of biological (e.g., species selection) and socioeconomic (e.g., extension techniques) aspects are needed to address this constraint.

Fodder Bank and Improved Fallow Systems

For enhanced soil fertility replenishment through fodder banks and improved fallows, due attention should be paid to proper choice at the tree species selection stage especially with regard to the characteristics of their root system (preference for deep-rooted species to reduce competition with crops and enhance nutrient cycling from deeper soil horizons) and the management practices (tree density, frequency of pruning, time of biomass application for better synchrony with maximum crop uptake, etc.). Furthermore, although fodder banks are appealing to farmers since they address both soil fertility and livestock productivity constraints, the risk of transfer of soil fertility in the case of exportation of biomass for fodder needs to be emphasized. The optimum quantity of biomass which can be harvested and transferred during the fallow period needs to be estimated. The transport and use of the

resulting farm yard-manure to the place where biomass was collected also need attention. A move in the right direction would be research programs which promote the use of native as well as exotic multipurpose trees that are well known to farmers. It is believed that much more can and has to be learned about these species in their overall contribution to soil fertility replenishment. The species selection and improvement procedures need a shift in emphasis: instead of focusing on performance of individual species (as in conventional species-improvement efforts), the emphasis should be on performance of the overall system (combine productivity of the system vs individual components). Yet another aspect is the role of the association of root-micorrhizal fungi. Through the expansion of the contact surface of fine roots, the potential of micorrhizae in increasing the uptake of fixed-soil P may be exploited to overcome P limitations of these low-base-status soils.

Use of Linear Programing (LP) as Decision Making Support

Low-input, family-based farming systems are characterized by little or no access to resources, technology, cash, and information, their preoccupation of feeding the family rather than producing surplus for the market, and their risk aversion. They operate in fragile environments where their integrated activities are strongly constrained/determined by socioeconomic (eating habits, road infrastructures, markets, prices, etc.), biophysical (crop varieties/yield potentials, soil fertility aspects, etc.), and institutional (policy makers objectives, land tenure and natural resource management systems, research and extension supports, etc.) constraints.

The outcome of household decision-making can be widely different from the objectives as defined by policy makers. Household objectives may be in conflict with social goals, differ among households, and may not converge. Kruseman and Bade (1998) state that decisions are basically made by agricultural households, taking into account their own objectives, availability of resources, institutional arrangements and access to markets. For example, a resource-limited household may well be interested in maximizing both crop/vegetable production and livestock

activities to achieve subsistence goals, though such activities may conflict in terms of sharing the available resources or may conflict with sustainability objectives because of poor planning or lack of information and support. Numerous examples of such conflicts have been reported throughout the tropics where most of resource-poor household farming systems are found (Kaoneka and Solberg, 1997; Hengsdijk et al., 1998; Salinas et al., 1999).

The diversity and complexity of these farming systems, the extreme fragility of the environments where they have evolved, and the necessity of sustaining the use of natural resources for future generations call for the use of sophisticated scientific tools and, as stated by Hengsdijk et al. (1998), interdisciplinary research efforts in which knowledge and information from different viewpoints are integrated and synthesized. Such efforts have resulted in model-based analysis tools which use different objectives, resource availability, and constraints at varying scales (household, village, region, nation) to simulate prevailing conditions, predict the likely impacts the adoption of new technologies would have on specific farming systems or households, and their policy implications. These quantitative systems analysis (QSA) tools (Hengsdijk et al., 1998) include linear programming (LP), sensibility/

adaptability analysis (AA) (Hildebrand, 1996), farm household modeling (FHM) (Kruseman and Bade, 1998), risk analysis, etc., and they have been used in the tropics as an aid to support decision making at different levels and policy formulation.

Coulibaly et al. (1998) used a farm-programming model to simulate the expected effects of devaluation of the local currency (CFA) on cereal production in the Sudanian region of Mali. They reported that farmers were able to shift production in response to price signals from devaluation. The model's results indicated that with post-devaluation prices of 1996, real farm profit increased by 26%, making the households able to internally generate further investments in improved technologies. Continued investments in intensification are expected since estimated rates of return of the farm programming model were 500 to 600% for the intensive sorghum technology. They concluded that African farmers diversify rather than intensify their production because poor policies have ignored agriculture with their emphasis on urban or industrial sectors. These policies have twisted the price structure against domestic producers and reduced the profitability of agriculture. Consequently, farmers have been hesitant to make investments in more intensive technologies. As policy implications, their research points out that attention

needs to be directed to (i) developing input markets and new marketing uses of traditional cereals such as for bread, beer, and ultimately animal feed, and (ii) improvement of infrastructure to facilitate commodity flows from rural to urban areas.

In a study in the Cercle of Koutiala, located in the southern part of Mali and covering an area of 91000 km^2 Kruseman and Bade (1998) used a linear programming (LP) framework for the selection of production activities, i.e., crop, livestock, and technology choices. Taking into account the available resources, specific production activities for arable cropping, livestock and pasture management are selected that satisfy farm household objectives. Multiple objectives are considered in the model to account for consumer preferences (consumption utility) and sustainability criteria (macro-nutrients and OM balances).

The results of their study showed that OM balances were strongly negative, indicating the high incidence of soil mining practices in the area. Full equilibrium of OM balances cannot be reached because part of the currently applied (unsustainable) technologies offered attractive short-term income prospects. Access to improved technological options was constrained at farm household level because of limited availability of information, risk

aversion or high transaction costs. Therefore, if further adoption of better cropping practices that improve both agroecological sustainability and net revenue is desired, additional policy incentives should be identified. They also indicated that the current policy environment imposes strong constraints for improving welfare and sustainability. By providing only better access to technology, the problem of ongoing resource degradation cannot be solved. Combinations of "economic incentives" and "appropriate technology" can slow down the process of soil degradation but further market reform and structural policies are required to offer adequate incentives to farmers to adopt more intensive and sustainable farming practices. Similar results were reported by Hengsdijk et al. (1998) from the same region.

From other parts of the tropics, Kaoneka and Solberg (1997) applied mathematical programming (LP) and welfare maximization theory to analyze the effect of population growth on agriculture/forest land use competition, per capita cash income and subsistence consumption from privately owned farms as a basis to determine the economic sustainability of the present farming systems in the West Usambara Mountains, Tanzania. The analysis indicated that the present farming systems can sustain the present population growth and per capita income for a maximum

duration of only 30 years, life expectancy being over 45 years. Thus, the farming systems cannot support even one human generation. Further, population growth is likely to accelerate deforestation. Indications for policy measures were (i) improvement of farming technology to meet increased food demands while limiting expansion of farmlands through forest clearing, (ii) enhancement of the welfare of rural populace, and (iii) proper family planning to mitigate population growth vis-à-vis economic growth. Salinas et al. (1999), successfully used a LP model to optimize system net income in a goat production system at the whole-farm level in Mexico. They generated several scenarios varying the prices (before and after devaluation), subsidy policy, and the use of technology (traditional and recommended). The model did perfectly simulate the situation by selecting a maize-bean cultivated area of 64 ha in conditions of good prices and subsidy policy. However, when the subsidies were removed, the model output was only 8 ha. They found that the traditional technology was more versatile to goat meat and maize stubble's price changes and concluded that the scenarios presented expressed the rationality in the process of decision making by farm owners.

The few examples from the region and many others from other regions indicate the potential of LP as a decision

making tool in farming system studies. These examples are the result of multi-disciplinary research called for in the development of more robust scientific tools to simulate the behavior of resource-limited farm households when it comes to the adoption or non adoption of improved technologies. These tools give solid scientific background information for politicians and decision-makers in policy formulation. However, these quantitative systems analysis (QSA) tools have some major drawbacks (Hengsdijk et al., 1998). First, when applied in exploratory studies, these tools are useful for the identification of new opportunities and bottlenecks and for priority setting, but they do not address the actual implementation of policy instruments to attain desired changes. Second, although some of these tools suggest they are interactive, there is little proof of this claim. From these two observations, it is clear that more challenges have to be faced in order to make better use of the analytical tools we have developed.

Conclusion

Soil fertility decline is perceived to be a major constraint limiting food production in semiarid SSA. The many traditional tree-based land-use systems people have relied on for years to replenish soil fertility and support

agricultural production are now being challenged by many social and technical constraints. While shifting cultivation is pushed up to its limits by severe human and animal pressure (reduced fallow length, continuous cultivation), the parkland system is a victim of ageing of trees. And, both systems are victims of "the tragedy of the commons" in a region where common management of land resources is the norm. The scientific advances in the field of agroforestry might be better exploited to increase the potential of trees to replenish soil fertility. Based on the mechanisms of increased nutrient supply, increased nutrient availability, and improved soil properties, new technologies such as fodder banks and short-rotation planted fallows are potential candidates in soil fertility replenishment. However, the scientific evidence gathered so far on these technologies are inadequate. There is a need for more research in the region to explore the potentials of improved technologies.

CHAPTER 3
SOIL PROPERTIES AND MAIZE PRODUCTION IN AN ON-FARM TRIAL OF IMPROVED FALLOWS WITH THREE SPECIES AT N'GOUKAN, MALI.

Introduction

The farming systems in the Koutiala region are focused on crop and animal husbandry. Major crops include cereals (maize--*Zea mays*, sorghum--*Sorghum bicolor*, millet--*Pennisetum typhoides*) and cash crops (cotton, and peanut). They have evolved in a parkland system with long bush fallows well known for their beneficial contribution to soil fertility replenishment (Kater et al., 1992; Kessler, 1992; Kwesiga and Coe, 1994). Cotton and, to a lesser extent, maize, receive organic (manure, household waste, compost) and/or chemical inputs (fertilizers and pesticides). Other cereal crops seldom receive any fertilizer. The rapid population growth during the past two decades has resulted in intense land use pressure, which, together with the unsustainable land tenure/ownership rights, has disrupted the traditional parkland system. As a result, soil fertility has declined and crop yields have decreased drastically in the region (Pieri, 1992; van der

Pol and Traoré, 1993; Breman and Kessler, 1995; Smaling and Braun, 1996; Sanchez et al., 1997). Although new and supposedly more sustainable land-use technologies including erosion control measures, production and/or utilization of organic and inorganic sources of soil nutrients, and improved land-preparation techniques such as ridging have been developed, they are poorly adopted by farmers. Infrastructural limitations, overall economic backwardness, and lack of favorable policy incentives are cited as the main reasons for this worsening situation (Coulibaly et al., 1998; Kruseman and Bade, 1998; Shapiro and Sanders, 1998).

It is infeasible to continue the present system of farming that leads to soil fertility mining (van der Pol, 1992; van der Pol and Traoré, 1993). In that context, soil-improving agroforestry technologies have great potential as a means of enhancing soil fertility. One such technology on which attention has been focused is the improved fallow. An improved fallow consists of deliberately planted species, usually legumes, with the primary purpose of fixing N_2 as part of a crop-fallow rotation (Sanchez, 1999).

The research presented here is a part of the research initiative in improved fallows in southern Mali. The hypothesis we intended to test in this research was: the association of fast-growing woody and herbaceous species

provides soil protection and contributes to nutrient recycling, resulting in overall soil productivity enhancement in a relatively short time (3-4 years) compared with the traditional natural fallows (up to 15 years). The specific objective is to identify the most suitable woody and herbaceous species for an agroforestry system and determine how they contribute, solely and in association, to soil fertility improvement through short-term fallows in the southern Mali region of Koutiala.

Materials and Methods

Description of the Study Area

The experiment was conducted from 1996 to 1998 as an on-farm trial at N'Goukan, a village located in the southern Mali Koutiala region, 25 km southeast of Koutiala (12.25^{0} N, 5.42^{0} W; 650 to 850 mm of annual, unimodal rainfall; classified as a Typic Plinthustalf soil). The soil texture of the top 30 cm is sandy loam becoming finer textured at depths of 50 to 100 cm (Vlot and Traoré, 1995). It is highly leached, has distinct horizons underlaid with hard pans rich in iron oxides, is impoverished of nutrients, is low in organic matter (OM), and is highly prone to severe sheet erosion. The rainy season runs from

June to October. The amount of rain received at N'Goukan in 1998 was 846 mm (Figure 3.1).

Experiment Setup, Management, and Sampling Scheme

Fallow phase

The experimental design is a randomized complete block (RCBD) with three replicates. There were two woody multipurpose trees (MPT) [*Gliricidia sepium* (Jacq.) Walp. (gliricidia) and *Pterocarpus erinaceus* Poir.(pterocarpus)] and one herbaceous species [*Stylosanthes hamata* (L.) Taub.(stylosanthes)]. The woody species were raised in a container nursery for three months. There were six treatments:

T1: *Gliricidia sepium*

T2: *Gliricidia sepium* + *Stylosanthes hamata*

T3: *Pterocarpus erinaceus*

T4: *Pterocarpus erinaceus* + *Stylosanthes hamata*

T5: *Stylosanthes hamata*

T6: natural grass fallow (control).

The individual plot size was 16 m x 16 m. Prior to seeding and planting, 300 kg ha^{-1} of Tilemsi rock phosphate (locally known as PNT) was applied uniformly to the site to boost legume growth and nodulation, considering the low P

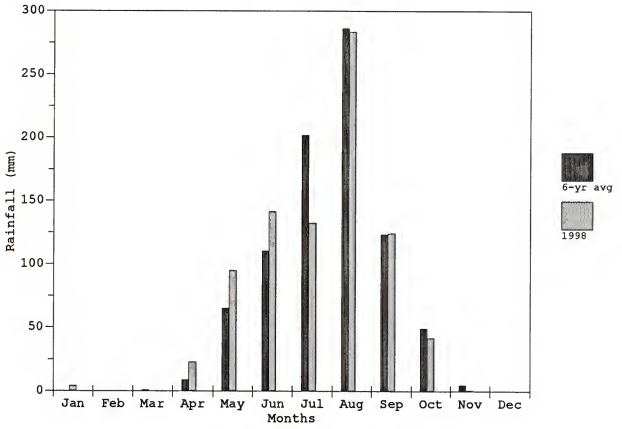

Figure 3.1. Rainfall at N'goukan, Koutiala.

availability of the soils at the site. Scarified *Stylosanthes hamata* seeds were broadcast at the rate of 15 kg ha^{-1} and tree seedlings were planted at 4 m x 2 m spacing (1,250 trees ha^{-1}). An ordinary ox plow was used to prepare the seed bed at medium-depth plowing (10 to 15 cm) after the first rains in 1996.

The experiment was fenced off during the fallow phase to avoid damage from free-grazing cattle. Weeding was performed in 1996 around the young tree seedlings to minimize competition between proliferating natural grasses and the planted MPTs. The woody species were allowed to grow normally during the whole fallow phase. Seedling growth parameters (height and diameter) and survival rate for gliricidia and pterocarpus, as well as dry matter (DM) production of stylosanthes were estimated in 1997 and in 1998. Faced with fodder constraints, the collaborating farmers cut the stylosanthes at the end of the rainy season and fed it to cattle in 1997 before data were collected.

Cropping phase

At the end of the fallow period in June 1998, the experiment was continued to assess the impact of different treatments on soil properties, maize DM production and grain yield. Trees were cut off at 30 to 40 cm above soil

surface and the resulting total fresh biomass weighed. Sub-samples were collected, weighed fresh, air-dried for 2 to 3 days and at 65°C for 48 hours to constant weight, and weighed again to determine the DM. Large branches were removed for use as fuel while the leafy materials, twigs, and small branches were applied to the soil surface and plowed under during seed bed preparation, together with all other existing plant materials present on the plot at that time (stylosanthes and/or natural grasses) to serve as a source of nutrients for the maize crop.

An estimation of the contribution of *S. hamata* above- and below-ground biomass to the total applied DM was made for treatments containing this species. For the above-ground DM, a 1-m^2 frame was randomly sampled five times, cutting the fresh material at soil surface in each plot. One kg sub-samples were dried for DM determination and the data extrapolated to a hectare basis. The estimation of the below-ground (root) biomass was done by digging five randomly selected 0.25-m x 0.25-m frames up to 65- to 80-cm depth where most of the roots are located. One-mm mesh plastic bags were used to carry the entire soil and wash it off with rainwater to separate the roots. The entire root mass was then collected and weighed fresh and dried as described previously for tree samples. The volume of the

excavated soil was used to compute the below-ground biomass. A local variety of maize (*Sotubaka*) was planted in June at 0.8-m x 0.5-m spacing yielding 25,000 hills ha^{-1} thinned to two plants per hill. No mineral source of nutrients was applied.

Plant sampling

Each plot was subdivided into two equal subplots one of which was reserved for the estimation of the grain yield while the other was used for plant sampling. Precaution was exercised not to sample two consecutive plants in order to avoid creating large gaps which might affect normal growth of the maize plants. Five to ten maize plants were randomly collected from each plot at 6, 9, 12, and 15 weeks after planting (WAP) and weighed fresh. They were then air-dried on a concrete floor in a ventilated room for 5 to 7 days and at 65°C for 48 hours to constant weight, and weighed to determine the DM. At harvest (15 WAP) the grain was harvested from the yield sub-plot, dried on concrete floor for several weeks and weighed. The yield was expressed in kg ha^{-1}.

Soil sampling and analysis

Soil samples were taken using a Dutch auger in June 1996 at 0- to 10-cm depth before the experiment was set up. Samples were again taken in June 1998 before applying the fresh biomass and in October 1998 after maize crop harvest at 0- to 20-cm, 20- to 40-cm, and 40- to 60-cm depths. Five core samples were collected from each 16 m x 16 m plot (1 m away from the edges) for each depth and thoroughly mixed. A representative 1-kg subsample was taken, air-dried, ground, and sieved through 2-mm mesh sieve. All particles greater than 2 mm were discarded. Laboratory analyses were carried out at the Sotuba Laboratoire Sol-Eaux-Plante, Bamako, Mali. Unfortunately, we were unable to find the samples collected in June 1986 by our predecessors and they were not analyzed.

Available P was determined according to the Bray-2 method, total N with the Kjeldahl method, and pH using a 1:2.5 (g soil/mL water) suspension with a pH meter. Organic carbon was determined with di-chromate sulfuric acid and Mohr's salt. Ammonium acetate, 1 N at pH 7.0, was used to displace the exchangeable cations. Calcium and magnesium in the extract were determined by atomic absorption spectrophotometry and potassium was measured using a flame-

photometer. Cation exchange capacity was determined using neutral, normal neutral ammonium acetate.

Statistical analysis

The data were analyzed (ANOVA) by SAS (SAS Institute, 1988) using the PROC GLM procedure for a randomized complete block design with three replicates. The treatment means were separated by LSD and they were declared different at $P < 0.05$.

Results

MPT Survival, Growth Rate, and Production of DM

There were no differences among treatments in terms of MPT survival which was greater than 90% three months after planting. However, survival declined by 6 to 8% for Treatments 1, 2, and 3 and by 19% for Treatment 4 in 1997. The decline was more pronounced in 1998 (> 30%) for Treatments 2 and 4 where gliricidia and pterocarpus were associated with stylosanthes (Table 3.1). There was complete ground cover from 1997 with stylosanthes contributing from 10% of the species in Treatments 1, 3, and 6 (where it was not planted) to more than 90% in

Treatments 2, 4, and 5 (Table 3.1). The local grass species, which contributed the most to ground cover were *Alisicarpus ovalifolius*, *Borreria* sp., *Digitaria horizontalis*, *Paspalum scrobiculatum*, and *Pennisetum pedicellatum*.

In terms of total biomass production, the treatments were different in 1997, but not in 1998. The dry matter produced ranged from 5000 to 7000 kg ha^{-1}. However, the bulk of this DM was contributed by annual indigenous grasses low in N.

Maize Dry Matter and Grain Yield

Maize stover production in the different treatments was in the following order Treatment 1 = Treatment 2 = Treatment 5 > Treatment 4 > Treatment 6 = Treatment 3 (Table 3.2). Treatment 2 resulted in the highest grain yield (2893 kg ha^{-1}) followed by Treatment 1 but the difference was not significant. Treatments 4 and 5 yielded similar amounts but greater than Treatments 3 and 6. A single degree of freedom contrast analysis (Table 3.3) revealed that the average maize grain yield achieved by Treatments 1 and 2 was superior to the one achieved by Treatments 3 and 4. However, neither Treatment 1 nor

Table 3.1. Growth rate and production of biomass of MPTs and the contribution of stylosanthes on improved fallows at N'Goukan in the Koutiala region, Mali.

Treatments	Survival rate		Biomass		Contribution of stylosanthes to total DM (%)
	1997	1998	1997	1998	
	------ (%) -----		---- kg ha^{-1} ----		
G. sepium	92	83	3900	6610	11
G. sepium + S. hamata	94	67	6670	5280	69
P. erinaceus	94	83	3150	6810	13
P. erinaceus + S. hamata	81	70	7220	6940	93
S. hamata			7370	6740	99
Grass fallow			1810	6880	11

Treatment 3 was superior to Treatment 5. In average all treatments where MPT biomass was applied yielded more maize grain than the control.

Soil Changes

For all the measured parameters (pH, C, N, and P) there were no differences among the treatments and across depths for the 1998 samples except for N (Table 3.4). The pH values varied from 5.7 to 6.6. Soil organic matter and N contents were very low, ranging from 1.4 to 3 g kg^{-1} for C and less than 2 g kg^{-1} for nitrogen. Phosphorus showed a trend of gradual decrease with depth; however, even the richer top soil layer was in the deficiency range.

The results from the sampling conducted at harvest are presented in table 3.5 as differences between those and the June 1998 values. There was a pattern of increase for the measured parameters (C, N, and P), however, differences were detected only for C and N levels for Treatment 1 and for P in the top soil layer for Treatment 4.

Table 3.2. Stover production and grain yield of maize in 1998 at N'Goukan in the Koutiala region, Mali.

Treatment	Stover	Grain yield	Grain yield increase relative to regional average yield
	------- kg ha^{-1} ------		(%)
*G. sepium**	7022 a	2170 ab	8
G. sepium + *S. hamata*	7071 a	2893 a	45
P. erinaceus	3019 c	0734 c	- 63
P. erinaceus + *S. hamata*	6596 ab	1540 bc	- 23
S. hamata	7322 a	1469 bc	- 26
Grass fallow	4081 c	714 c	- 64
P	0.01	0.01	

*Treatment means followed by the same letter are not statistically different at $P < 0.05$.

Table 3.3. Maize grain yield from contrasts comparing different species and natural grass fallow in 1998 at N'Goukan in the Koutiala region, Mali.

Parameter	Estimate	P > T
	-- kg ha^{-1} --	
G. sepium vs *P. erinaceus*	1394	0.005
G. sepium vs *S. hamata*	700	ns
P. erinaceus vs *S. hamata*	-735	ns
MPTs vs natural grass fallow	1046	0.03

Table 3.4. Soil fertility parameters at N'Goukan, Mali, in June 1998 before planting.

Parameter	Depth (cm)	Treatments					
		1	2	3	4	5	6
pH	0 to 20	6.30 a	6.18 a	5.76 a	5.69 a	5.68 a	6.11 a
	20 to 40	6.59 a	6.05 ab	6.04 ab	5.84 b	6.02 ab	5.90 b
	40 to 60	6.59 a	6.04 a	6.06 a	5.84 a	5.85 a	5.92 a
C	0 to 20	1.43 a	3.23 a	1.67 a	2.20 a	1.90 a	1.50 a
(g/kg)	20 to 40	2.27 a	2.30 a	1.30 a	1.27 a	1.87 a	1.67 a
	40 to 60	2.23 a	1.83 a	1.37 a	2.30 a	2.70 a	1.37 a
N	0 to 20	0.10 b	0.20 a	1.67 ab	0.20 a	0.20 a	0.13 ab
(g/kg)	20 to 40	0.10 b	0.17 ab	0.17 ab	0.13 ab	0.13 ab	0.20 a
	40 to 60	0.13 a	0.17 a	0.17 a	0.17 a	0.17 a	0.17 a
P	0 to 20	24.45 a	8.45 a	6.89 a	10.54 a	4.16 a	2.86 a
(mg/kg)	20 to 40	4.94 a	2.99 a	2.08 a	2.60 a	1.56 a	1.69 a
	40 to 60	4.55 a	1.82 a	1.82 a	1.95 a	1.43 a	1.43 a

Treatments followed by the same letter (s) are not significantly different at $P < 0.05$.

Treatments:
1 = *Gliricidia sepium*; 2 = *Gliricidia sepium* + *Stylosanthes hamata*;
3 = *Pterocarpus erinaceus*; 4 = *Pterocarpus erinaceus* + *Stylosanthes hamata*;
5 = *Stylosanthes hamata*; 6 = natural grass fallow.

Table 3.5. Changes in soil fertility parameters at N'Goukan, Mali: difference between June 1998 (before planting) and October 1998 (at harvest) values.

Parameter	Depth (cm)	Treatments					
		1	2	3	4	5	6
C	0 to 20	-2.90 **	-0.23 ns	-0.67 ns	-0.03 ns	-1.30 ns	-0.80 ns
(g/kg)	20 to 40	0.37 ns	0.33 ns	-0.77 ns	-0.53 ns	-1.77 ns	-0.57 ns
	40 to 60	0.67 ns	0.53 ns	-0.03 ns	1.50 ns	1.30 ns	0.13 ns
N	0 to 20	-0.13 **	0.00 ns	0.00 ns	-0.07 ns	0.03 ns	-0.03 ns
(g/kg)	20 to 40	-0.10 *	-0.03 ns	-0.03 ns	-0.07 ns	-0.10 *	0.00 ns
	40 to 60	-0.03 ns	0.00 ns	-0.07 ns	-0.10 ns	-0.07 ns	-0.07 ns
P	0 to 20	13.97 ns	0.15 ns	0.64 ns	-7.22 *	-3.37 ns	0.43 ns
(mg/kg)	20 to 40	-5.87 ns	-0.61 ns	-0.62 ns	-1.65 ns	-1.01 ns	-0.11 ns
	40 to 60	-0.59 ns	-0.37 ns	-1.27 ns	-3.45 ns	-0.63 ns	0.02 ns

Difference: ns = not significant, * significant at $P < 0.05$, ** significant at $P < 0.001$.

Treatments:
1 = *Gliricidia sepium*; 2 = *Gliricidia sepium* + *Stylosanthes hamata*;
3 = *Pterocarpus erinaceus*; 4 = *Pterocarpus erinaceus* + *Stylosanthes hamata*;
5 = *Stylosanthes hamata*; 6 = natural grass fallow.

Discussion

The high survival rates recorded three months after planting (Yossi et al., 1998) indicate that both species are well adapted to the local conditions of N'Goukan. However, there was a severe decline in tree survival rate after two years of growth, in 1998. This can be attributed to harsh competition of stylosanthes which literally strangled the woody species during the 1998 dry season as was evidenced by the presence of dead trees in the plots at the time of seed bed preparation in June 1998.

Gliricidia suffered more than pterocarpus from this competition. Pterocarpus, being a locally adapted species may endure and even tolerate competition from stylosanthes and natural grasses. This characteristic is of great interest for fallow-improving species in this region where labor limitations may seriously constrain weeding. However, pterocarpus did not contribute to total biomass because the plants were still very small two years after planting and therefore were not pruned. *P. erinaceus*, selected by the collaborating farmers for its quality-fodder, is well known for its slow early (first five years) growth. During that period, the species develops a strong root system. At age 10 to 15, pterocarpus would be mature enough to support

regular lopping in the wild, which is a common practice in Mali and in the neighboring countries, for supplying fodder to small ruminants during the dry season (ICRAF, 1996). From a pterocarpus fodder bank experiment at 1-m x 1-m spacing at Nyekentoumou (12^0 31' N, 7^0 30' W, 800 mm mean annual rainfall) near Bamako, Mali, Sidibé et al. (1997) reported production of 1880, 2630, 1270, and 2340 kg DM ha^{-1} respectively in March, April, May, and June during its fifth year of establishment. This indicates that the species can be domesticated and managed to improve its growth rate and biomass production. However, it is not a good candidate for short-rotation fallows of less than three years.

Gliricidia had survival and growth rates, respectively, greater than 80% and 90%. This species has an above-average DM production potential in the region but only when competition is minimized through weeding for at least the first two years. Its poor resistance to weed invasion means that more labor would be required for its establishment and management, which may affect its acceptability by farmers of the region as a fallow-improving species.

Stylosanthes hamata has proven to be very adapted to the local environment and quite productive in terms of DM.

Tarawali et al. (1997) indicated that the natural habitats for stylosanthes are usually soils of low fertility, especially low P, mainly of acidic nature, as is true of those at the experiment site. Most *stylosanthes* species tend to be of a promiscuous nodulating type, thus, inoculation is usually unnecessary. Edye and Grof (1984) reported that the species performed well under both drought and waterlogged conditions. In the subhumid zone of Nigeria, Tarawali and Peters (1997) reported forage yield of 10600 kg ha^{-1} after two years of growth, while Diarra et al. (1994) reported 5490 kg ha^{-1} at three years of age in the Koutiala region (Mali). Groot et al. (1995) reported stylosanthes DM production of 8360 kg ha^{-1} and 10860 kg ha^{-1} without and with P application, respectively. Thus, our findings in terms of DM are in the range of the potential production for the species.

Stylosanthes competes very well with local grasses. It is even invasive; after only two seasons of growth, it almost completely smothered other species in plots where it was planted and started invading the neighboring ones. These characteristics make the species a good candidate for easy establishment as a soil cover in the region. However, its ability to take up N from deeper soil layers may be hindered by its relatively shallow rooting depth. During

below ground sampling, we found more than 80% of the roots in the top 80 cm. However, in a study conducted in the same region on the root systems of three fodder species (*Andropogon gayanus*, *Stylosanthes hamata*, and *Vigna unguiculata*--cowpea) Groot et al. (1995) found that the distribution of root biomass of stylosanthes with depth was more homogenous than for the others, and root densities were high throughout the whole soil profile up to a 140-cm depth. Specific root length increased from 35 m g^{-1} for the 0- to 10 cm-layer to 100 m g^{-1} for the 130- to 140 cm-layer. They also indicated that the presence of high root length densities throughout the whole soil profile allowed efficient use of water and nutrients, and was especially important to satisfy the P requirement of the crop.

Maize grain yield increased by 8% in the gliricidia treatment and 45% in the gliricidia + stylosanthes treatment over the average yield for the Koutiala region, which was estimated to be 2020 kg ha^{-1} (ESPGRN, 1998). This indicates that sole gliricidia and the mixture of gliricidia and stylosanthes have great potentials as management options for maize production in the region. Although the association perocarpus/stylosanthes and sole stylosanthes have yielded less than the region's 1998 average, the yield they achieved is interesting enough to

merit their further consideration. The quantity of biomass applied in the sole pterocarpus treatment was similar to that applied in the natural grass-fallow treatment, which consisted mainly of annual grasses. Their inherent low N concentration might have resulted in poor growth and yield of maize. Thus, the sole pterocarpus and the traditional grass fallow treatments may not be recommended to be used in short-rotation fallows.

The soil analysis data revealed the extremely low fertility of the soils in the Koutiala region. The tendency of positive soil nutrient balances between June (before planting) and October (at harvest) values may indicate the beginning of an improvement. However, it is worth mentioning that it was not possible to compare the results with the initial values at planting of the fallow in 1996 because the samples taken then were not available to us for analysis. It may well be possible that these changes were triggered by the decomposition and nutrient release processes from the biomass applied at the onset of the cropping season. Notwithstanding the more than average maize grain yields achieved by some treatments in this experiment and the lack of initial soil analysis data, it is unlikely that these results may have come only from the observed levels of soil nutrients. Apart from release of nutrients (mainly N) these yields may, in part, be

explained by better growing environment. Indeed the plots were kept clean of weeds reducing competition for water and nutrients. We have also observed less water stress, especially on treatments where stylosanthes was present (T2, T4, and T5) perhaps because of better soil water holding capacity induced by the quantity of the applied biomass.

Conclusion

The findings from this experiment indicate that none of the species, taken alone, is an ideal candidate for soil fertility replenishment through improved fallows in the southern Mali Koutiala region. However, each has one or more desirable characteristics as a fallow-improving species. While *G. sepium* has high growth rate, production of good-quality biomass, and relatively deep rooting, it requires additional labor for weeding during the first two to three years of establishment. *P. erinaceus*, though well adapted, deep-rooted, and competition-tolerant, is slow growing and may not produce enough biomass in the time horizon of 3 to 4 years of improved fallows in the conditions of Koutiala. *Stylosanthes hamata*, proven to be well adapted to the local conditions, and drought- and

weed-tolerant, may be constrained by its shallow rooting depth in soil nitrate uptake. Thus, the best opportunity resides in a combination of species.

For short duration fallows the combination gliricidia / stylosanthes has great potential if the standing stylosanthes biomass is reduced. This implies cutting stylosanthes at the end of the rainy season to allow gliricidia to achieve a competition-free growth during the dry season. This is in conformity with the farmers' objective of supplying quality-fodder to cattle during the dry season. However, much more research is needed to find out the optimum quantity to be cut to prevent nutrient transfer and to assess the profitability of the system in terms of investment in management and labor. If the fallow length is more than seven years, the combination pterocarpus / stylosanthes could be the best option both in terms of investment in labor, management, and soil fertility replenishment. In any case, a two-year fallow duration is unlikely to bring about any significant change in soil fertility status. A more reasonable fallow length needs to be worked out by further research.

CHAPTER 4
SOIL PROPERTIES AND MAIZE (*ZEA MAYS*) PRODUCTION AS AFFECTED BY THE TRANSFER OF DIFFERENT-QUALITY BIOMASS AT N'TARLA, MALI

Introduction

There is growing interest in using plant residues and other locally available materials for improving soil productivity in farming systems in the tropics that are characterized by low external inputs (Buresh and Cooper, 1999). The addition of organic materials from outside the crop field is a nutrient input, although such transfer of biomass may involve some mining of nutrients at another site. The effectiveness of these organic materials as a source of nutrients depends to a large extent on their chemical composition (Swift et al., 1979). Many authors have shown that the decomposition and nutrient release patterns of organic materials are related to factors such as lignin and polyphenol concentration, N, C, and P concentration, and different ratios between these factors (Vallis and Jones, 1973; Fox et al., 1990; Palm and Sanchez, 1991; Mafongoya et al., 1997). However, there is no general agreement on any single factor which would be

the best predictor. To better predict the effects of plant residues on soils and crops, Tian et al. (1995) proposed a plant residue quality index which integrates key biomass characteristics known for their impact on decomposition and nutrient release, i.e., C/N ratio, lignin, and polyphenol concentration.

Accelerated soil fertility decline and search for ways to replenish the lost fertility have created strong interest in the use of residues of common crops (cereals and cotton) as a means of cycling of nutrients. Using the crop residues as beddings in cattle pens, and collecting and applying the resulted manure to crop fields is one way of recycling crop residues. Dry-season composting of residues has also been suggested. However, because of reduced availability of water in the region, composting requires a longer time (compost available only every other year) than transforming the residues through cattle pens, where the combined actions of the animals' urine, defecation, and trampling accelerate the decomposition process and enrich the end product. Bosma et al. (1993) even advocated increasing cattle numbers to sustain the production systems in the region, though they recognized that the actual stocking rate of 0.32 tropical livestock units (TLU) ha^{-1} is far beyond the carrying capacity of 0.13 to 0.15 TLU ha^{-1}. They recommended more intensive

animal husbandry less dependent on natural and degraded pasture lands with the necessary introduction of improved fallows, which would translate into an increase of the actual carrying capacity.

Improved fallows, involving introduction of fast-growing, high-quality, biomass-producing multipurpose tree (MPT) species planted to short (3 to 4 year) fallows and incorporation of their biomass into the soil before planting the crops, are known to improve nutrient cycling and soil fertility (Batiano et al., 1991; Tarawali, 1991; Kwesiga and Coe, 1994; Mafongoya et al., 1997).

We hypothesize that the incorporation of tree biomass grown outside the crop fields would improve soil fertility at least to the same extent as when multipurpose trees are grown and their biomass incorporated *in situ*. The objectives of this study are (i) to understand the decomposition and nutrient release patterns of *Gliricidia sepium* (Jacq.) Walp. (gliricidia), *Pterocarpus erinaceus* Poir. (pterocarpus) and *Stylosanthes hamata* (L) Taub. (stylosanthes), three species with potential for use in short-term fallows under the conditions of the southern Mali Koutiala region, and (ii) to assess the effectiveness of the incorporation of "imported" high-quality biomass

compared to its *in situ* application on the improvement of soil fertility and maize crop production.

Materials and Methods

Description of the Study Area

The study was conducted at the N'Tarla research station, 45 km northwest of Koutiala (12.25^0 N latitude, 5.42^0 W longitude). The only annual rainy season is from June to October with rainfall varying from 650 to 850 mm yr^{-1}. The average rainfall received at N'Tarla for ten years from 1988 to 1997 is about 885 mm while the 1998 rainfall was 970 mm (Figure 4.1). The soil at the station is a Typic Plinthustalf with a loamy-sand texture in the top 40 cm, becoming finer-textured as one moves down the profile with inclusions of 15-30% gravel at depths of 70 to 95 cm (Vlot and Traoré, 1995). It is highly leached, has distinct horizons underlain with hard pans rich in iron oxides, impoverished of nutrients, low in organic matter (OM), and highly prone to severe sheet erosion.

Experiment Setup, Management, and Sampling Scheme

Application of biomass

The experiment was conducted for two consecutive years (1997 and 1998) using biomass collected from three MPT species (gliricidia, pterocarpus, and stylosanthes) grown off-site. The design was a RCBD with nine treatments replicated three times. The biomass was applied at two different rates. Rate 1, equivalent of 50 kg N ha^{-1}, was calculated from the N concentration of the species and the conservative assumption that only 30% of the N released upon decomposition will be effectively available for crop uptake (Mulongoy, 1986; Mulongay and van der Meersch, 1988; Kang, 1988; Balasubramanian and Sekayange, 1992). Rate 2 is equivalent of the dry matter production potential of each species at three-to-four years of age (target length of the improved fallows) in the conditions of the Koutiala region of southern Mali. The N content of rate 2 was 59, 16, and 48 kg N ha^{-1} for gliricidia, pterocarpus and stylosanthes, respectively. The treatments were all factorial combinations of the three levels of species with the two rates, the recommended rate of manure (10 t ha^{-1} for three years), a farmer-practiced rate of mineral fertilization of maize [100 kg urea ha^{-1} + 50 kg of a 15-15-15 ($N-P_2O_5-K_2O$)

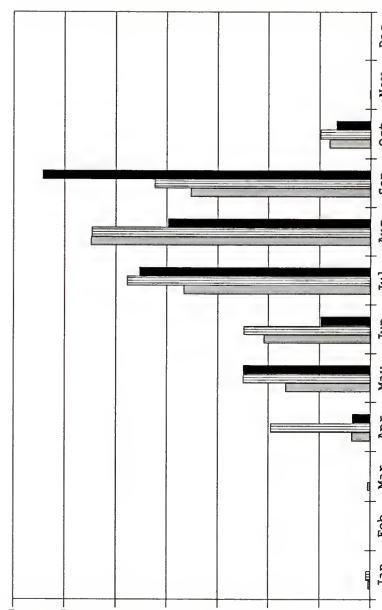

Figure 4.1. Rainfall pattern at the N'Tarla research station, Mali.

fertilizer ha^{-1}], and natural control with no added nutrients.

The biomass was applied in 1997 at the time of land preparation before sowing. The materials consisted of sun-dried leaves, twigs, and small branches of the species collected from existing plantations. The biomass was uniformly applied to the soil surface and incorporated at a 10- to 15-cm depth with an ox-drawn plough. In 1998, the plots were split into two subplots. Biomass was applied at the corresponding rate on one subplot for the assessment of the effect of the application of biomass for two consecutive years while none was applied to the other for the assessment of the residual effects of the biomass applied in 1997. In all cases the applied biomass was the only source of nutrients for maize for T1 through T6. Manure was not applied to T7 but the same rate of mineral fertilizers was applied to T8 in 1998. A local maize variety (*Sotubaka*) was planted at 0.8-m X 0.5-m spacing and thinned to 2 plants per hill yielding a population of 50,000 plants ha^{-1}.

Plant sampling and analysis

There were five sampling dates: 4, 6, 9, 12, and 15 weeks after planting (WAP). At each sampling date, one hill

(1 to 2 plants) was randomly sampled from each plot 2 to 5 cm above ground. Except at the first sampling date, the plant material was separated into different parts (leaves, stem, and grains). The parts were first sun dried and then oven dried at 65°C to constant weight, to determine the dry matter (DM). They were finely ground (1 mm), placed in *Nasco* WHIRL-PAK plastic bags, and stored at room temperature before analysis. They were analyzed separately for total N (Carlo Erba Instruments NA1500 Nitrogen/Carbon/Sulfur Analyzer, Italy) at the University of Florida, Gainesville. The N concentration (%) and the corresponding DM weight were used for each sampling date to compute maize N uptake (kg ha^{-1}). At harvest, the grain from the subplot was harvested, sun-dried on a concrete floor for several weeks to determine the grain yield in kg ha^{-1}.

Decomposition study

The litter bag technique recommended by the Tropical Soil Biology and Fertility Programme (Anderson and Ingram, 1993) was used to assess the decomposition and nutrient release patterns of the biomass from the three MPT species used in the experiments. Twenty-gram, dry-biomass samples were placed in 1-mm mesh 20-cm x 30-cm litter bags (90 in

total) and buried at 15- to 20-cm depth in each treatment. One bag was sampled at each of the five sampling dates when maize plants were sampled (4, 6, 9, 12, and 15 WAP). All detectable external solid materials (soil, plant residue) and plant/crop roots (which penetrated the litter bags) were carefully removed by hand. The content of the litter bags (undecomposed litter) was collected and oven-dried at 65^{0}C to constant weight. The dry weight was recorded and used to compute the decomposed litter fraction. The undecomposed material was analyzed at the University of Florida, Gainesville for total N and C. The rate of mineralization was computed as follows:

$$\%\ of\ original\ N\ content = \frac{\%\ N_t}{\%\ N_0} * \%\ DW\ ,$$

where N_t and N_0 represent N at time t and at the initial time, respectively, and DW represents the material remaining in the litter bag at time t, expressed as a percentage of the initial DM weight.

% of N released = 100 - % of original N remaining.

Crop N uptake efficiency (NUE)

We used the results of maize N and the N release from MPT biomass (from the decomposition study) to compute maize N uptake efficiency (NUE) as follows:

$$\%NUE = \frac{Total\,N_{treatment} - Total\,N_{control}}{Total\,Napplied} * 100\ ,$$

where Total $N_{treatment}$ and Total $N_{control}$ are the total N (kg ha^{-1}) in the treatment and control plots, respectively.

Soil sampling and analysis

Soil samples were taken at 0- to 20-cm, 20- to 40-cm, and 40- to 60-cm depths in June 1997 before the experiment was set up and in October 1997 after maize crop harvest. Five core samples were collected from each plot (1 m away from the edges) for each depth and thoroughly mixed. A representative 1-kg subsample was taken, air-dried, and sieved through 2-mm mesh size sieve. All particles greater than 2 mm were discarded. Samples were similarly drawn in June and October 1998. Laboratory analyses were carried out at the Laboratoire Sol-Eaux-Plante de Sotuba, Bamako, Mali. Procedures for soil chemical analysis are the same as the ones described in Chapter 3.

Statistical analysis

The data were analyzed (ANOVA) by SAS (SAS Institute, 1988) using the PROC GLM procedure for a randomized complete block design with three replicates. The treatment means were separated by LSD and they were declared different at $P < 0.05$.

Results

Maize Dry Matter and Grain Yield

There were differences among the treatments both in 1997 and 1998 except for the residuals in 1998 (Table 4.1). In 1997, T7 (manure) produced the greatest amount of DM followed by T8 (fertilizer). For the biomass-applied treatments, the production was in the order (stylosanthes = gliricidia) > pterocarpus; higher rates (T2, T3, and T5) yielded more than the lower ones (T1, T4, and T6). In 1998, when biomass was added for a second consecutive year, the ranking shifted to the following order (T1 = T2) > (T3 = T8) > (T 4 = T6) > (T5 = T9) > T7. There were no differences among the treatments for their residual effects in 1998 though the manure (T7) and control (T9) treatments yielded lower DM figures as compared to the others. The DM production of maize at different sampling dates showed significant differences only at 12 and 15 WAP in 1997 and at 6 and 15 WAP in 1998 for the biomass-applied treatments.

Analysis of the maize grain yield data revealed differences among treatments both in 1997 and in 1998 (Table 4.1). Only the gliricidia-biomass applied treatments resulted in yields higher than the region's average grain yield of 2000 kg ha^{-1} in 1997. They were followed in the

Table 4.1. Dry matter production and grain yield of maize in 1997 and 1998 at the N'Tarla research station, Mali.

Treatment	Dry matter			Grain Yield		
	1997	1998		1997	1998	
		Residual	Biomass		Residual	Biomass
	----------	kg ha^{-1}	----------			
G. sepium 1[α]	3910 cd	6151	12596 a	2225 ab	1757	3450 ab
G. sepium 2[β]	4761 bc	8959	13538 a	2575 a	2003	4110 ab
P. erinaceus 1	3521 cd	5882	11250 abc	1273 cd	1637	2917 bc
P. erinaceus 2	1633 e	5910	9100 abcd	486 d	1320	2147 cd
S. hamata 1	4589 bc	5609	6538 cd	1436 bc	2600	1687 de
S. hamata 2	4306 bcd	6795	7993 abcd	1229 cd	1820	1887 de
Manure	8366 a	4875	4875 d	1116 cd	2070	2070 cd
Fertilizer	5714 b	11453	11458 ab	1688 bc	2567	2567 cd
Trad. Fallow	2759 de	5264	5264 cd	404 d	990	990 e
P	0.0001	ns	0.05	0.04	ns	0.04

[α] Rates 1 indicate quantities of dry-matter (kg) capable of releasing 50 kg N ha^{-1} upon decomposition for each species. [β] Rates 2 indicate an estimate of the dry matter production potential (kg ha^{-1}) at three years of age for each species in the conditions of the Koutiala region. Treatment means followed by the same letter(s) are not significantly different at $P < 0.05$.

order:(T8 = T5) > (T3 = T6 = T7) > (T4 = T9). A similar trend was observed in 1998 on the biomass-applied treatments. For the residual effects, the high rate of stylosanthes (T5) and the fertilizer-applied (T8) treatments yielded similar amounts which were significantly higher than the others.

Maize N Uptake

The amount of N taken up by maize was assessed at different sampling dates in 1997 and 1998. There were no differences among the treatments in 1997 with a range from 1.2 to 5.0 kg N ha^{-1} at 4 WAP to 28 to 91 kg N ha^{-1} at harvest. However, lower figures were always associated with the low rate of *P. erinaceus* and the control treatments (Table 4.2). The trend was the same in 1998 for the residual-effect treatments, but lower figures were associated with low rates of the 1997-applied biomass (T1, T3, and T6), manure (T7), and control (T9) treatments (Table 4.3). The maximum N uptake for these residuals was very low compared to the 1997 figures and never exceeded 50 kg N ha^{-1} indicating that the crops were under severe N deficiencies. Maize N nutrition was much better in 1998 biomass-applied treatments. There were differences among the treatments 6 WAP and at harvest (Table 4.4). At 6 WAP,

gliricidia (T1 and T2) treatments had the highest total N uptake followed by the fertilizer and the low rate of pterocarpus. The other treatments were similar and yielded lower N figures. At harvest, the ranking was T2 > T1 > (T3 = T4) > (T5 = T6 = T8) > (T7 = T9).

Table 4.2. N uptake of maize under different treatments at the N'Tarla research station experiment, Mali, 1997.

	Sampling dates in weeks after planting				
Treatments	**4**	**6**	**9**	**12**	**15**
	----------	----------	**kg ha^{-1}**	----------	----------
G. sepium 1	2.98	16.46	27.88	29.09	60.19
G. sepium 2	4.78	18.82	39.07	48.10	62.70
P. erinaceus 1	2.65	14.10	22.62	41.02	67.76
P. erinaceus 2	1.43	6.59	7.77	11.33	30.50
S. hamata 1	4.02	18.60	22.21	62.90	62.02
S. hamata 2	5.12	14.77	31.69	30.79	55.75
Manure	3.12	10.30	23.06	55.53	91.41
Fertilizer	5.41	17.55	26.99	45.30	84.82
Trad. Fallow	1.20	4.07	13.40	22.43	28.44
P	ns	ns	ns	ns	ns

Treatment means followed by the same letter(s) are not significantly different at $P < 0.05$.

Table 4.3. N uptake of maize under different treatments at the N'Tarla research station experiment, Mali, 1998 (residuals).

Treatments	Sampling dates in weeks after planting				
	4	6	9	12	15
	----------	----------	kg ha^{-1}	----------	----------
G. sepium 1	5.07	12.59	17.19	15.47	34.32
G. sepium 2	2.54	10.18	16.16	14.48	41.90
P. erinaceus 1	3.77	12.14	26.91	25.19	36.18
P. erinaceus 2	3.88	8.69	21.13	18.16	36.31
S. hamata 1	2.76	10.20	13.65	16.95	34.94
S. hamata 2	3.28	14.53	16.66	32.70	15.45
Manure	3.92	8.29	14.48	31.82	27.45
Fertilizer	11.93	19.84	42.81	35.16	46.64
Trad. Fallow	4.83	4.41	15.67	9.59	16.05
P	ns	ns	ns	ns	ns

Treatment means followed by the same letter(s) are not significantly different at $P < 0.05$.

Table 4.4. N uptake of maize under different treatments at the N'Tarla research station experiment, Mali, 1998 (biomass applied).

Treatments	Sampling dates in weeks after planting				
	4	6	9	12	15
	----------	----------	kg ha^{-1}	----------	----------
G. sepium 1	8.09	27.31 ab	18.31	27.57	75.15 ab
G. sepium 2	7.99	31.59 a	45.45	38.41	92.53 a
P. erinaceus 1	1.55	14.21 bcd	31.61	22.87	53.45 abc
P. erinaceus 2	4.48	18.06 abcd	21.55	31.81	48.67 abc
S. hamata 1	3.94	9.17 cd	27.11	28.98	38.66 bc
S. hamata 2	2.35	10.95 cd	34.60	24.26	44.34 bc
Manure	3.93	8.29 cd	14.18	31.82	27.45 c
Fertilizer	11.93	19.84 abc	42.81	35.16	46.64 bc
Trad. Fallow	4.83	4.42 d	15.67	9.59	16.05 c
P	ns	0.02	ns	ns	0.04

Treatment means followed by the same letter(s) are not significantly different at $P < 0.05$.

Rate of Decomposition of Biomass

The rate of decomposition of the applied biomass from the different species was monitored for two consecutive years at the N'Tarla research station. On average, gliricidia lost more than 50% of the initially applied biomass by 4 WAP while the loss was only 45% for stylosanthes and less than 30% for pterocarpus. At the end of the 15-week-growing season, the undecomposed material was 13% for gliricidia, 30% for pterocarpus and 26% for stylosanthes. Overall, gliricidia was the fastest decomposing material followed by stylosanthes, and lastly pterocarpus (Figure 4.2).

Maize N Uptake Efficiency

Figure 4.3 presents a two-year average of the difference between the amount of N released upon decomposition of the applied biomass and the quantity of N present in maize at different sampling dates. Overall, there was an excess of N during the first 6 WAP, a nearly steady balance from weeks 9 to 12, and a large deficit afterwards. The excess was more pronounced for the fast decomposing materials, i.e., gliricidia and stylosanthes. At 4 WAP, the excess of N released by gliricidia and

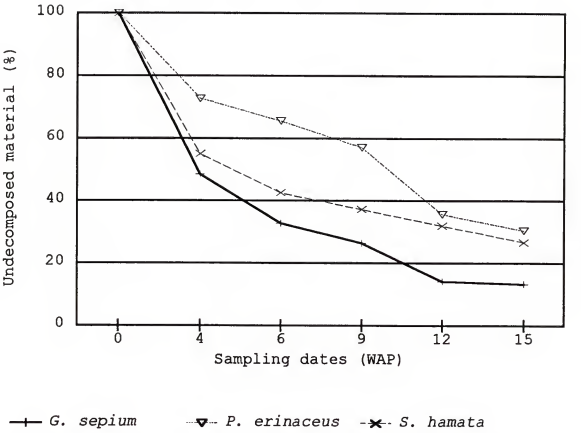

Figure 4.2. Decomposition pattern of MPTs at N'Tarla, Mali, 1997 and 1998.

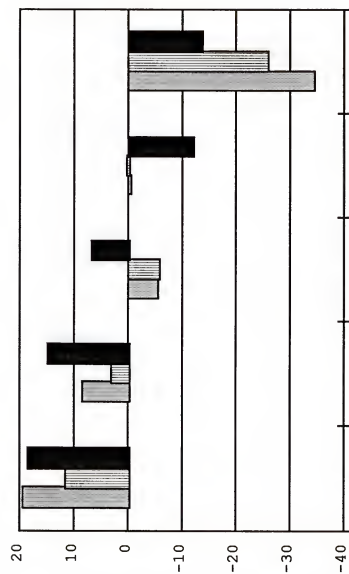

Figure 4.3. Difference between N release by MPTs and maize N uptake at N'Tarla, Mali, 1997 and 1998.

stylosanthes was nearly 20 kg ha^{-1} vs only 10 kg ha^{-1} for pterocarpus. Towards the end of the growing season the greatest N deficit was recorded on gliricidia applied treatments (35 kg ha^{-1}). The deficit was 28 kg ha^{-1} and 15 kg ha^{-1} for pterocarpus and stylosanthes treatments respectively.

Soil Aspects

At the beginning of the experiment in June 1997 the soil was uniform in its chemical aspects at all three depths (Table 4.5). The pH values varied from 5.6 at 40- to 60-cm depth to 6.1 at 0- to 20-cm depth with an average of 6.0 making this soil slightly acidic. The C and N concentrations were very low. The low C concentration associated with low OM concentration explains partially the poor structure and the extreme susceptibility to erosion of the soils at the N'Tarla research station. Phosphorus values ranged from 8 to 24 mg kg^{-1} for the 0- to 20-cm depth. These values decreased gradually in the 20- to 40-cm and 40- to 60-cm layers. Though P is recognized as one of the most limiting soil nutrients in the region, most of the values recorded in the upper soil layer at the research site were in the "medium range" of 13 to 25 mg kg^{-1} that might, in theory, support satisfactory crop yields. Indeed,

Table 4.5. Soil fertility parameters at N'Tarla, in June 1997 at the beginning of the experiment.

Parameter	Depth (cm)	Treatments								
		1	2	3	4	5	6	7	8	9
pH	0 to 20	6.04 a	5.89 a	6.02 a	6.04 a	6.02 a	6.09 a	5.96 a	5.97 a	6.07 a
	20 to 40	5.70 a	5.73 a	5.73 a	5.84 a	5.92 a	5.91 a	5.89 a	5.83 a	5.88 a
	40 to 60	5.62 a	5.66 a	5.70 a	5.85 a	5.94 a	5.90 a	5.81 a	5.76 a	5.73 a
C	0 to 20	2.90 a	3.83 a	3.47 a	2.73 a	3.57 a	3.57 a	2.47 a	4.33 a	3.20 a
(g/kg)	20 to 40	2.53 a	3.07 a	2.37 a	2.43 a	2.57 a	2.27 a	4.43 a	3.83 a	3.90 a
	40 to 60	4.43 ab	3.00 b	3.20 ab	3.43 ab	3.57 ab	5.47 a	3.50 ab	2.77 b	2.20 b
N	0 to 20	0.24 a	0.25 a	0.26 a	0.24 a	0.26 a	0.26 a	0.29 a	0.23 a	0.25 a
(g/kg)	20 to 40	0.21 ab	0.21 ab	0.24 a	0.20 b	0.21 ab	0.22 ab	0.22 ab	0.20 b	0.20 b
	40 to 60	0.23 a	0.20 a	0.25 a	0.22 a	0.22 a	0.21 a	0.22 a	0.22 a	0.23 a
P	0 to 20	16.72ab	15.02 ab	12.61 ab	15.85 ab	8.08 b	11.90 ab	10.91 ab	14.52ab	13.18ab
(mg/kg)	20 to 40	7.51 a	4.82 a	5.10 a	6.38 a	3.40 a	5.39 a	5.39 a	7.79 a	3.97 a
	40 to 60	2.13 a	2.13 a	1.77 a	2.97 a	2.69 a	2.27 a	2.41 a	3.26 a	1.56 a
CEC	0 to 20	1.60 b	1.82 ab	1.82 ab	1.75 ab	2.12 ab	1.68 b	2.10 ab	4.79 a	2.98 ab
(cmole/kg)	20 to 40	2.09 a	2.11 a	2.77 a	1.97 a	2.63 a	2.70 a	2.63 a	2.78 a	2.73 a
	40 to 60	4.64 ab	3.59 ab	4.60 ab	4.23 ab	4.38 ab	4.08 ab	4.35 ab	3.42 b	5.21 a
Na	0 to 20	0.04 a	0.18 a	0.19 a	0.23 a	0.11 a	0.01 a	0.31 a	0.18 a	0.44 a
(cmole/kg)	20 to 40	0.007 a	0.06 a	0.13 a	0.08 a	0.11 a	0.12 a	0.05 a	0.34 a	0.13 a
	40 to 60	0.01 b	0.03 ab	0.10 ab	0.20 ab	0.07 ab	0.06 ab	0.06 ab	0.37 a	0.15 ab

Treatments followed by the same letter (s) are not significantly different at $P < 0.05$.

Table 4.5 (continued). Soil fertility parameters at N'Tarla, in June 1997 at the beginning of the experiment.

Parameter	Depth (cm)	Treatments								
		1	2	3	4	5	6	7	8	9
K	0 to 20	0.18 ab	0.20 ab	0.26 a	0.17 ab	0.23 a	0.20 ab	0.22 a	0.13 b	0.19 ab
(cmole/kg)	20 to 40	0.13 ab	0.13 ab	0.16 a	0.11 ab	0.14 ab	0.09 b	0.14 ab	0.09 b	0.10 ab
	40 to 60	0.13 ab	0.32 a	0.15 ab	0.13 ab	0.19 ab	0.12 ab	0.11 b	0.08 b	0.10 b
Ca	0 to 20	0.83 a	1.02 a	1.10 a	1.02 a	0.72 a	0.76 a	0.98 a	0.87 a	0.96 a
(cmole/kg)	20 to 40	0.98 ab	1.06 ab	1.36 a	0.69 b	0.87 ab	0.82 ab	1.17 ab	1.01 ab	1.08 ab
	40 to 60	1.41 a	1.33 a	1.53 a	1.24 a	1.20 a	1.61 a	1.37 a	1.26 a	1.41 a
Mg	0 to 20	0.24 a	0.29 a	0.26 a	0.18 a	0.22 a	0.23 a	0.29 a	0.18 a	0.24 a
(cmole/kg)	20 to 40	0.27 bc	0.31 abc	0.38 ab	0.22 c	0.27 bc	0.26 bc	0.41 a	0.27 bc	0.30abc
	40 to 60	0.78 a	0.78 a	0.91 a	0.73 a	0.75 a	0.79 a	0.78 a	0.56 a	0.84 a

Treatments followed by the same letter (s) are not significantly different at $P < 0.05$.

fertilizer and manure application is a current management practice at the research station; thus, minimizing P deficiency problems.

When the soil was analyzed after two growing seasons (residual effects) in October 1998 there was a general decline in all the measured soil parameters (Table 4.6). A comparison between the June 1997 and June 1998 values (Table 4.7) indicated that the decline had indeed started even before the end of the second growing season for some parameters. The decline was more pronounced for N with statistically significant differences between the June 1997 and the June 1998 values at all three depths. The C concentration was reduced for the fertilizer-applied treatment (T8). The results for P were not consistent across the different depths. A slight decline was observed for the P values which was significant only for the fertilizer-applied treatment at the 0- to 20-cm depth. A non significant trend toward increasing P levels was observed for the 20- to 40-cm layer and to a lesser extent at 40- to 60-cm depth. On the other hand, there was a general tendency of increasing soil pH (except for treatments 1, 2, and 9 at the top soil layer) and CEC (except for treatments 4, 8, and 9 at the 0- to 20-cm depth). However, the trend was not statistically significant.

Table 4.6. Soil fertility parameters at N'Tarla, in October 1998 (residual effects).

Parameter	Depth (cm)	Treatments								
		1	2	3	4	5	6	7	8	9
pH	0 to 20	5.41 b	5.62 b	5.61 b	5.63 b	5.67 b	5.70 b	5.73 b	5.53 b	6.19 a
	20 to 40	5.09 cd	5.20bcd	5.08 d	5.24bcd	5.27abcd	5.33abcd	5.62 a	5.46abc	5.56 ab
	40 to 60	4.91 a	5.30 a	4.89 a	5.19 a	5.17 a	5.04 a	5.53 a	5.50 a	5.21 a
C	0 to 20	2.17 ab	2.18 ab	2.53 ab	0.86 b	2.17 ab	3.20 ab	4.43 a	2.67 ab	2.00 ab
(g/kg)	20 to 40	3.93 a	3.13 a	3.13 a	3.10 a	3.18 a	2.67 a	2.53 a	2.40 a	2.53 a
	40 to 60	3.53 a	3.55 a	3.55 a	4.27 a	3.13 a	3.90 a	2.03 a	2.33 a	3.70a
N	0 to 20	0.20 ab	0.23 ab	0.23 ab	0.17 b	0.23 ab	0.27 a	0.23 ab	0.23 ab	0.23 ab
(g/kg)	20 to 40	0.10 b	0.10 b	0.13 ab	0.10 b	0.10 b	0.13 ab	0.13 ab	0.17 a	0.17 a
	40 to 60	0.17 a	0.15 a	0.15 a	0.17 a	0.17 a	0.13 a	0.17 a	0.17 a	0.17 a
P	0 to 20	9.58 b	6.64 b	7.99 b	17.24 a	8.30 b	8.81 b	9.45 b	10.47 b	10.35 b
(mg/kg)	20 to 40	2.56 a	2.81 a	3.06 a	2.55 a	2.30 a	2.43 a	3.08 a	3.61 a	3.34 a
	40 to 60	1.79 a	1.53 a	2.30 a	1.53 a	2.04 a	1.92 a	2.57 a	2.83 a	2.58 a

Treatments followed by the same letter (s) are not significantly different at $P < 0.05$.

Table 4.7. Changes in soil chemical parameters at the N'Tarla research station, Mali expressed as difference between initial (June 1997) and final (June 1998) stages.

Parameter	Depth (cm)	Treatments								
		1	2	3	4	5	6	7	8	9
N	0 to 20	0.04 ns	0.12 **	0.10 *	0.14 **	0.09 *	0.06 *	0.09 **	0.06 *	0.02 *
(g/kg)	20 to 40	0.11 **	0.08 *	0.17 **	0.10 **	0.08 *	0.09 **	0.06 *	0.10 **	0.07 *
	40 to 60	0.07 *	0.03 ns	0.15 *	0.12 **	0.12 **	0.11 **	0.06 *	0.12 **	0.13 **
P	0 to 20	4.66 ns	0.57 ns	0.95 ns	14.52 ns	0.12 ns	1.56 ns	-1.32 ns	10.53**	-1.20 ns
(mg/kg)	20 to 40	2.47 ns	-2.21 ns	-1.13 ns	-2.77 ns	-1.5 ns	1.04 ns	-2.37 ns	1.61 ns	-4.05 ns
	40 to 60	-0.26 ns	-0.52 ns	-0.75 ns	0.19 ns	0.31 ns	0.03 ns	-0.36 ns	0.24 ns	-0.68 ns
K	0 to 20	-0.01 ns	0.02 ns	0.07 ns	0.01 ns	0.01 ns	0.03 ns	0.04 ns	-0.01 ns	0.02 ns
(cmol/kg)	20 to 40	-0.06 ns	-0.03 ns	-0.02 ns	-0.04 ns	-0.05 ns	-0.03 ns	-0.09 ns	-0.08 ns	-0.06 ns
	40 to 60	-0.05 ns	0.18 ns	0.01 ns	0.03 ns	-0.07 ns	-0.01 ns	-0.10 ns	-0.06 ns	-0.03 ns
C	0 to 20	0.33 ns	1.47 ns	1.80 ns	0.07 ns	1.63 ns	0.90 ns	-0.17 ns	2.80 *	0.80 ns
(cmol/kg)	20 to 40	-0.23 ns	0.77 ns	0.07 ns	0.10 ns	0.30 ns	0.47 ns	2.57 ns	2.30 *	1.10 ns
	40 to 60	2.60 ns	0.83 ns	0.43 ns	2.17 ns	1.07 ns	3.70 *	1.80 ns	-0.20 ns	0.93 ns
CEC	0 to 20	-0.83 ns	-0.65 ns	-1.27 ns	0.00 ns	-1.03 ns	-0.67 ns	-0.55 ns	1.21 ns	0.73 ns
(cmol/kg)	20 to 40	-0.14 ns	-4.04 *	0.10 ns	-0.30 ns	-0.37 ns	-0.11 ns	-0.38 ns	0.04 ns	-0.59 ns
	40 to 60	-1.72 ns	-2.74 ns	-0.88 ns	-0.36 ns	-0.79 ns	0.17 ns	0.05 ns	-0.85 ns	1.30 ns

Difference: ns = not significant, * significant at $P < 0.05$; ** significant at $P < 0.001$

Discussion

Maize DM and grain yields were higher in 1998 than in 1997 (Table 4.1). Apart from the treatment effect, better rainfall distribution conditions in 1998 also may have contributed to this. Although there was more total rain, 1122 mm, in 1997 than in 1998, 970 mm, the distribution was better in 1998. The DM produced in 1998 was higher when tree biomass was applied for the second consecutive year as compared to not applying it in the second season. For gliricidia, the increase was 51% more for the high rate (T2) while the DM more than doubled for the low rate (T1) of application. The opposite occurred with pterocarpus with a 91% increase in maize DM yield for the high rate (T3) vs 54% for the low rate (T4). Stylosanthes resulted in an almost identical increase of maize DM yield 16% and 18% for high (T5) and low (T6) rates respectively.

Although these results are not conclusive, it appears that one-time application of large quantities of biomass is less advantageous than repeated (annual) applications of smaller quantities in the Koutiala region. It is well documented that the annual decomposition rate of soil organic carbon (k) is higher in arid and semiarid tropical climates than in temperate regions (Sanchez, 1976; Nair, 1993; Tisdale et al., 1993). In general, the higher the

clay content and the higher the proportion of oxides and allophane, the lower will be the k values. Also, because the average annual temperatures are nearly constant in the tropics, decomposition takes place year-round. Since k increases with temperature and aeration, cultivation increases the rate of disappearance of soil organic carbon. Sanchez (1976) reported decomposition rates as high as 6.6% on continuous peanut cultivation in neighboring Senegal as compared with average k rates of 1.2% in tropical savannas. Soils at the research station are Alfisols characterized by their low base status and their coarse texture (69% sand). The combination of these factors may have contributed to accelerated decomposition of the biomass applied at land preparation in 1997. Most of this decomposition may have happened during the four-to-five-month rainy season when soil temperatures and humidity are ideal for microbial activity and may not have left any significant quantity of biomass for decomposition the following year. In such conditions, repeated applications of small quantities may be more beneficial. Annual applications of 5000 kg DM ha^{-1} of leguminous MPT species seems to be able to sustain maize grain yields comparable to the application of fertilizers in the Koutiala region, especially if P is not deficient. Indeed, it is well known that the contribution of

agroforestry trees to crop P nutrition is very limited (Jama et al., 1998; Sanchez and Palm, 1996).

Maize grain yield doubled for all treatments where biomass was applied for a second consecutive year as compared to the residual effects. However, there was no difference between high and low rates for the same species, suggesting that a moderate application rate of about 5000 kg DM ha^{-1} would suffice to achieve maize grain yields similar to the average yield obtained with the traditional practices of manure or chemical fertilization in the region.

Both in 1997 and in 1998, the maximum N uptake was observed from 12 WAP with figures varying from 20 kg N ha^{-1} to as much as 90 kg N ha^{-1} for the MPT-applied treatments. Friedrich et al. (1979) and Mills and McElhannon (1982) reported that 60 to 70% of the total maize N uptake occurs after the onset of tasseling, which corresponds well with the period from 12 WAP in our situation. The poor performance of maize in the 1998 residual-effect treatments may well be explained by inadequate N nutrition.

Though there is no general agreement on any single plant tissue quality factor which would be the best predictor of the rate of decomposition of biomass, the scientific literature abounds with reports indicating the influence of single or a combination of many factors. C:N

ratio and the lignin are two of the most important factors that determine the rate of decomposition and they could well be among the best predicting factors (Nair et al., 1999). It is also established that soil factors (type, humidity, pH, aeration, microflora, etc.), climatic conditions (temperature, rainfall), time of application and placement methods of biomass (surface application or incorporation) determine to a great extent what the rate of decomposition would be (Becker et al., 1994; Mafongoya et al., 1997). In our experiment, we have opted for incorporation at the onset of the rainy season at seed bed preparation. This mode of placement has proven to favor better decomposition under similar climatic conditions in Zimbabwe (Mafongoya, 1995) and is more practical in the Koutiala region's farming practices. The fastest decomposing material, gliricidia, has a C:N ratio of 14.7 while the ratios for pterocarpus and stylosanthes are 16.9 and 16.1, respectively. Tisdale et al. (1993) used a C:N ratio of 20:1 as a dividing line between N mineralization and immobilization. Considering C:N ratio and lignin concentration as two of the best indicators of biomass quality as noted earlier, the species used in our experiments have biomass of varying quality: they all had C:N ratios less than 20, but the lignin concentrations were 9.4%, 39.7%, and 9.5%, respectively for gliricidia,

pterocarpus, and stylosanthes. The high lignin concentration of pterocarpus may have delayed decomposition and N-mineralization from its biomass.

The efficiency of crop N uptake is determined by environmental conditions, the availability of N in the soil, and the crop growth stage. In the particular case of agroforestry in resource-poor farming systems, the decomposition of applied MPT biomass releases nutrients, mainly N, which are expected to ensure nutrition of companion or subsequent crops. Fast decomposing materials release large quantities of N very early in the growth period. This N is subject to losses through many processes such as leaching, volatilization, immobilization, and denitrification. The erosion loss is more on coarse-textured sandy soils especially when the release coincides with low crop N demand at young age with insufficient root system. The rationale of managing the timing and application methods of MPT prunings is to reduce the amount of N lost before optimum crop uptake through synchrony, i.e., matching release of nutrients in forms available to crop uptake from decomposing prunings to the crop's growth and demands (Swift, 1987).

Our findings indicate excess soil N of 19, 11 and 18 kg ha^{-1} at 4 WAP and 8, 3 and 14 kg ha^{-1} at 6 WAP, respectively, for gliricidia, pterocarpus, and stylosanthes

treatments (Figure 4.2). These results are consistent with the rate of decomposition of the species. Mafongoya et al. (1997) suggested a build up of soil N before the onset of maximum crop N demands for better synchrony while Myers et al. (1994) stated that improved synchrony implied that there was less quantity of excess available N in the soil minimizing the opportunity for loss. Though we did not assess the soil N budget and the dynamics of N movement in the soil, the amount of rainfall in the region (1122 mm in 1997 and 970 mm in 1998) and its distribution which do not favor anaerobic conditions resulting from flooding, and the soil pH of ≥ 5.5 suggest that N losses through leaching and volatilization were relatively low.

Availability of N to maize seems to have been nearly adequate from 9 to 12 WAP for all the MPT biomass-applied treatments. Towards the end of the growing season, there was a nitrogen deficit of 34, 26, and 14 kg ha^{-1} for gliricidia, pterocarpus, and stylosanthes treatments, respectively. Though it was clear that the remaining undecomposed material could not provide enough N to match crop demand and uptake at this stage, it was uncertain to what extent the early excess N contributed to this demand. The soil at the site being poor in N (0.02%) and assuming reduced N losses during the growing period, it may well be

possible that most of the crop N was derived from the "soil reserve" built up early in the season.

While very few researchers have studied the decomposition and N release patterns of pterocarpus and stylosanthes, gliricidia is among the most intensively studied MPT species for these aspects. Our results are in agreement with those of Tian et al. (1992), Oglesby and Fownes (1992), and Mafongoya (1995) who found gliricidia to decompose and release N rapidly. The addition of high- and low-quality biomass into the soil is reported to reduce the rates of decomposition and N release, hence, reducing losses and improving synchrony between N release and crop N demand. This process may well explain the results reported from the on-farm experiment at N'Goukan (Chapter 3) where the gliricidia + stylosanthes treatment yielded higher maize dry matter and grains than either of them alone.

The soil analyses revealed generally poor soil conditions at the research site. The general decline in soil N, P, and C concentrations after two cropping seasons indicate that soil mining takes place after the first year of application of biomass, especially with low rates as the ones applied for this experiment (2500 to 8000 kg DM ha^{-1}). However, soil P levels at the research site are assumed to be higher as compared to ordinary soils in farmers' fields. Thus, although maize P nutrition was not monitored, it is

speculated that P supply was adequate because no P deficiency symptoms were observed during the period of study.

Conclusion

The first objective of this study was to understand the decomposition and nutrient release patterns of *Gliricidia sepium*, *Pterocarpus erinaceus*, and *Stylosanthes hamata* under the conditions of the southern Mali Koutiala region. The results of this study clearly indicate that gliricidia biomass is the fastest decomposing material followed by stylosanthes and pterocarpus in that order. While gliricidia and stylosanthes are of high-quality biomass, the high lignin concentration of pterocarpus may have played a great role in the observed relatively slow decomposition rate.

The second objective of the study, to assess the effectiveness of the incorporation of "imported" high quality biomass compared to its *in situ* application on the improvement of soil fertility and maize crop production, is partially achieved by making use of the results from on-farm (Chapter 3) and on-station (Chapter 4) experiments. The application of biomass resulted in satisfactory crop

grain yields in both cases. Gliricidia + Stylosanthes treatments in on-farm trials (N'Goukan) and sole Gliricidia and stylosanthes treatments in the on-station experiment (N'Tarla research station) yielded more than the region's 1998 average maize grain yield of 2020 kg ha^{-1}. However, because changes in soil parameters are very slow and the experiments did not last long enough to detect any significant soil changes, the results are not fully conclusive.

Future researcher-managed improved fallows allowing longer fallow phases of three-to-four years in duration are highly recommended in order to conclusively answer the initial hypothesis. Because fodder is scarce in the region during the dry season and its limitation seriously constrains animal production, which is a strong component of the region's farming systems, such research may be coupled with the investigation of a "safe quantity of biomass" to be harvested from these fallows and fed to cattle before the end of the fallow period without jeopardizing the soil fertility objective. Likewise, the fate of biomass-derived soil N (using ^{15}N) is recommended to be investigated in the region.

CHAPTER 5
SOIL ORGANIC MATTER DYNAMICS FOLLOWING ADDITION OF BIOMASS OF DIFFERENT FALLOW-IMPROVEMENT SPECIES

Introduction

Soil fertility decline which has resulted in insufficient crop production in SSA in general and in the southern Mali region of Koutiala in particular has raised general awareness and is being addressed at many levels with varying technologies and management packages. The use of animal manure, household wastes, composts, and the application of biomass to sustain crop production through the building up or maintenance of soil organic matter (SOM) are already widely practiced by local farmers in the region. Palm et al. (1997) stress that the combined use of organic and inorganic nutrient sources offers the best alternative for soil fertility replenishment in SSA while Sanchez et al. (1997) advocate that replenishment of soil fertility in Africa is an investment in natural resource capital.

Numerous authors have reported on the important role that SOM plays in nutrient cycling in tropical ecosystems

(Sanchez and Miller, 1986; Nair, 1993; Woomer et al., 1994; Vanlauwe et al., 1998) especially in the low input farming systems of semiarid SSA. It can safely be assumed that soil organic matter concentration is one of the first key aspects to act upon in terms of management for enhanced and sustainable soil productivity in the tropics.

These attributes are well known to the farmers in the Koutiala region as denoted by the use of long fallows (when still feasible), domestic waste, farm-yard manure, and to a limited extent, crop residues. Animal husbandry has now become an integral part of the region's farming systems either as a result of investments of farm income in cash-crop systems or because of the movement of people from the northern belt of the country southward in response to frequent droughts. The consequent degradation of pasture lands and the necessity of preserving soil productivity (use of farm-yard manure) have favored new approaches to soil fertility management in the farming systems. Apart from the use of household waste, it is now common that, despite of the scarcity of land, farmers grow forage crops to feed part of their cattle herd. Agroforestry technologies such as fodder banks and improved fallows have high potentials to be effectively adopted by farmers and integrated in the newly evolving farming systems especially

now that they provide solutions to the animal husbandry and soil fertility depletion constraints.

Knowledge about the nature and turnover of SOM is a prerequisite for understanding the chemical reactivity and inherent fertility of soils, and for predicting the fate of mineral fertilizers, animal manure, and crop residues added to soil (Kristensen, 1992). However, in contrast to the especially well documented chemical aspects of SOM and microbially mediated processes, research on physical fractionation and organomineral complexes has been much less.

Soil fertility research has to be based on innovative and new approaches, rather than conventional soil analyses. For example, methods commonly used for measuring and characterizing SOM, such as organic C and humic acids, may be of limited use to understand the link between SOM dynamics and nutrient availability because they do not measure biologically active SOM fractions (Motavalli et al., 1994). Soil organic matter fractionation is one such approach that is now gaining acceptance as a better indicator in soil fertility studies. It is based on the observation that SOM in the sand-size fraction (>53 μm) is often more labile than SOM in the clay- and silt-size fractions (Tiessen and Stewart, 1983; Gregorich et al., 1988).

Kristensen (1992) indicated that SOM from different pools differed in composition and biological function. He also reported that the light SOM fraction (in the sand-size fraction) may contain up to 50 and 40% of total soil N and C, respectively, making it richer than the heavy fraction (in the clay- and silt-size fractions). Cambardella and Elliot (1992) termed the SOM sand-size fraction "particulate organic matter" (POM) and Vanlauwe et al. (1998) found highly significant relationships between residue-derived nitrogen (RDN) present in the POM and uptake of RDN by maize indicating the relatively high availability of RDN in POM. The effect of different agroforestry trees and practices on SOM fractions will therefore be well worth investigating.

Tisdale et al. (1993) report that it is more the quantity than the quality of the returned material that determines to what extent SOM can be improved. The knowledge of the dynamics of the added plant material, i.e., its evolution from large pools of organic materials to smaller-size fractions upon decomposition, and the contribution of each size fraction to crop nutrition would be an important scientific input in support of decision making for soil fertility management. For example, Barrios et al. (1996) reported a greater dry weight of SOM light fraction and greater amounts of N and C in the light

fractions either with rotation of cowpea (*Vigna unguiculata*) with maize or the seasonal addition of *Gliricidia sepium* prunings to continuous maize than from continuous cropping of maize with removal of crop residues. Through particle size-density fractionation, Maroko et al. (1999) reported from an experiment in Kenya that *Sesbania sesban* and natural fallows increased the amount of P in light fraction SOM as compared with maize monoculture and bare fallow.

All these results point to the fact that new analytical approaches are needed for the evaluation of the impact of SOM on soil properties and crop nutrition. The objectives of this study are (i) to assess the dynamic of the evolution in the soil medium of different quality organic materials in the Koutiala region, (ii) determine the contribution of different size-fractions to crop yield, and (iii) to select species most appropriate for crop nutrition and soil fertility replenishment.

Materials and Methods

The soil samples used in this experiment were collected from the N'Tarla research station in the Koutiala region of southern Mali. The general soil characteristics

at the research site and other experimental details were described in the previous chapter (Chapter 4). Samples were collected three times: in June 1997 before initiation of the experiment, in October 1997 after crop (maize) harvest, and a year later, in October 1998, after harvest of the second crop of maize. At each sampling date, five samples were collected from the 0- to 20-cm surface layer along diagonal transects 1 m away from the edges of the plot. They were bulked, homogeneously mixed, and a 1-kg subsample was retained for the analysis. There were 3 samples per treatment x 9 treatments x 3 sampling dates, yielding a total of 81 samples. The soil samples were air-dried, ground, and sieved through a 2 mm-mesh sieve; particles greater than 2 mm were removed and discarded.

The SOM fractionation, based on particle-size distribution after dispersion, was carried out at the Resource and Crop Management Division (RCMD) laboratory at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria in December, 1998, as described by Vanlauwe et al. (1998). One hundred grams of dry soil were dispersed in 100 mL of a sodium hexametaphosphate-Na_2CO_3 solution (35.7 g of sodium hexametaphosphate L^{-1} and 7.9 g of Na_2CO_3 L^{-1}) mixed with 400 mL of distilled water through shaking for 16 h on a reciprocal shaker adjusted to 144 revolutions min^{-1} (4.5-cm shaker amplitude). In preliminary tests, this

procedure was found to nearly disperse the soil up to 0.002 mm without causing an artificial, significant redistribution of organic matter from the larger particle-size classes toward the smaller particle-size classes. After dispersion, the soil slurry was wet-sieved on a wet-sieve shaker (Octagon 200, Endcotts, London, UK) to separate the fractions between 0.250 and 2.000 mm, between 0.053 and 0.250 mm, and <0.053 mm. The organic components were separated from the mineral fraction for each of these particle-size classes by careful decantation. The different fractions were referred to as follows:

M250: 0.250 to 2.000 mm mineral,

O250: 0.250 to 2.000 mm organic,

M53 : 0.053 to 0.250 mm mineral,

O53 : 0.053 to 0.250 mm organic.

The fraction <0.053 mm was not separated and it was designated MO20.

The organic fractions O53 and O250; i.e., 0.053 to 0.250 mm, referred to as POM (Cambardella and Elliot, 1992) were analyzed for total N and C (Carlo Erba Instruments, NA1500 Nitrogen/ Carbon/ Sulfur Analyzer, Italy) at the University of Florida, Gainesville. The MO20 fraction (made of silt and clay fractions difficult to separate from the organic fraction) and all the mineral fractions which yielded very low values in previous tests (Vanlauwe et

al., 1998; B. Vanlauwe personal comm., Dec. 1998) were not considered for subsequent analyses. The fractions which make up the POM (O53 and O250) are referred to hereafter as F53 and F250.

The data were analyzed statistically using SAS to perform analysis of variance (ANOVA), and contrast and correlation analysis. Treatment means were separated by the least significant difference (LSD) procedure and treatments were declared different at $P < 0.05$.

Results

Soil Particulate Organic Matter (POM)

The amount of OM contained in the medium-size soil fraction of 0.053 to 2.000 mm (POM) was not affected by treatments at any specific year (Table 5.1). The initial value, at the beginning of the experiment in June 1997, was close to 6000 kg ha^{-1}. The average values in October 1997 after the first-season crop's harvest ranged from 3767 kg ha^{-1} for the control treatment (traditional grass fallow) to 4850 kg ha^{-1} for the farm-yard manure treatment. A similar trend was observed a year later, in October 1998, both for the residual effects (R) and for the biomass-applied (B) treatments. However, when compared across

Table 5.1. Particulate organic matter (POM) and nitrogen content of POM (POM_N) in the topsoil (0 to 20 cm) at the N'Tarla research station (Mali) in 1997 and 1998.

Soil POM and POM_N (kg ha^{-1})	Treatments								
	1	2	3	4	5	6	7	8	9
	kg ha^{-1}								
POM 97	4117 a	4908 a	4450 a	4083 a	4042 a	4592 a	4850 a	4825 a	3767 a
POM 98 R	3292 a	4283 a	3858 a	3808 a	3575 a	4398 a	3992 a	4392 a	3125 a
POM 98 B	3242 a	4300 a	3517 a	3308 a	3458 a	4058 a	3992 a	4392 a	3125 a
POM-N 97	56.25 bc	80.21 a	58.23 bc	57.85 bc	58.11 bc	65.84 abc	70.73 ab	63.60 abc	48.36 c
POM-N 98 R	43.25 a	55.09 a	53.08 a	45.38 a	47.33 a	68.39 a	52.81 a	58.52 a	43.37 a
POM-N 98 B	45.89 a	61.71 a	50.85 a	38.13 a	45.31 a	56.86 a	52.81 a	58.52 a	43.37 a
POM-N across years	56.58 bc	69.48 a	60.77 abc	55.57 bc	57.94 bc	68.00 a	64.32 ab	65.39 ab	54.00 c

Treatments followed by the same letter (s) are not significantly different at $P < 0.05$. Treatments: 1 = *G. sepium* rate 1; 2 = *G. sepium* rate 2; 3 = *P. erinaceus* rate 1; 4 = *P. erinaceus* rate 1; 5 = *S. hamata* rate 1; 6 = *S. hamata* rate 2; 7 = farm yard manure; 8 = fertilizer; 9 = traditional grass fallow (control). R = residual effects; B = biomass applied for a second consecutive year.

different years, the average POM values had significant differences as compared to the initial soil POM content (Figure 5.1 and Table 5.2). The results of the contrast analysis (Table 5.3) indicated considerable decrease in soil POM from the June 1997 value. There were 26, 35, and 37% less POM, respectively, in October 1997 and in the 1998 residuals and biomass-applied treatments as compared to the initial value of June 1997. The application of biomass for two consecutive years (1997 and 1998) did not appear to have increased the soil POM content as compared to the residual effects, where biomass was applied in 1997 but not in 1998.

The analysis of the weight of different POM size classes indicated no difference among the treatments in any year (Table 5.4). The results revealed that the finer particle size, 0.053 to 0.250 mm, (F53) contributed more to the total soil POM weight than the larger size, 0.250 to 2.000 mm, (F250). However, there was a difference among treatments when values were averaged over time. For the F250 size class, the fertilizer (T8) and the farm-yard manure (T7) treatments yielded higher values than the others while the low rates of gliricidia (T1) and pterocarpus (T4) and the high rate of stylosanthes (T5) had the lowest ones. The remaining treatments were statistically identical in their F250 fraction weight. For

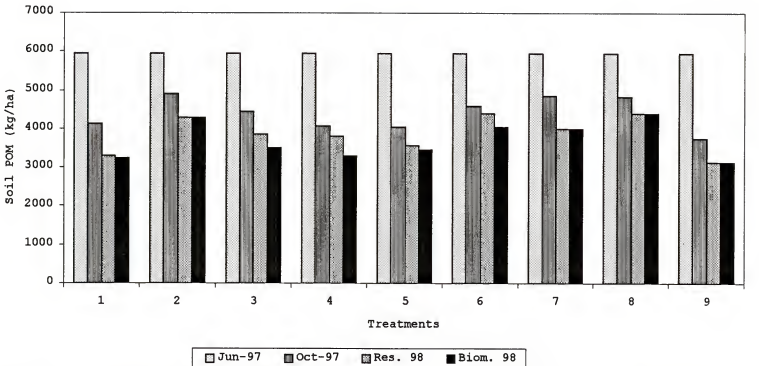

Figure 5.1. Particulate organic matter content of surface (0 to 20 cm) soil at different sampling dates at N'Tarla, Mali. See Table 5.1 for treatment description.

Table 5.2. Average weight and N content of particulate organic matter (POM) in surface soil (0 to 20 cm) at different sampling dates at N'Tarla, Mali.

Sampling dates	POM	POM-N
	kg ha^{-1}	
June 1997	5950 a	80.92 a
Oct. 1997	4403 b	62.13 b
Oct. 1998 (R)	3858 c	51.92 c
Oct. 1998 (B)	3710 c	50.38 c
P	0.0001	0.0001

Dates followed by the same letter(s) are not significantly different at P = 0.05; R = residual effects; B = biomass applied for a second consecutive year.

Table 5.3. Variation of soil particulate organic matter(POM) and POM nitrogen content as differences between averages at different sampling dates at N'Tarla, Mali.

Contrast	POM		POM-N	
	Difference (kg ha^{-1})	P	Difference (kg ha^{-1})	P
June 97 vs. Oct 97	1547	0.0001	18.79	0.0001
June 97 vs. Oct 98 R	2092	0.0001	29.00	0.0001
June 97 vs. Oct 98 B	2240	0.0001	30.54	0.0001
Oct. 97 vs. Oct 98 R	546	0.0160	10.21	0.0032
Oct. 97 vs. Oct 98 B	694	0.0160	11.75	0.0008
Oct. 98 R vs. Oct 98 B	148	0.5057	1.54	0.6473

R = residual effects; B = biomass applied for a second consecutive year.

Table 5.4. Different size fractions of soil particulate organic matter at the N'Tarla research station (Mali) in 1997 and 1998 for residual(R) and biomass applied (B)treatments.

Dates and Fraction size[1]	Fraction weight								
	Treatments								
	1	2	3	4	5	6	7	8	9
	kg ha^{-1}								
1997									
F250	1525 b	1975 ab	1825 ab	1475 b	1575 b	1567 b	2350 a	2158 ab	1700 ab
F53	2592 ab	2933 a	2625 ab	2608 ab	2467 ab	3025 a	2500 ab	2667 ab	2067 b
1998 R									
F250	1083 a	1325 a	1567 a	1200 a	1258 a	1242 a	1558 a	1942 a	1292 a
F53	2208 ab	2958 a	2292 ab	2608 ab	2317 ab	3157 a	2433 ab	2450 ab	1833 b
1998 B									
F250	1158 ab	1417 ab	1325 ab	975 b	1158 ab	1467 ab	1558 ab	1942 a	1292 ab
F53	2083 ab	2883 a	2192 ab	2333 ab	2300 ab	2592 ab	2433 ab	2450 ab	1833 b
Across time									
F250	1335 c	1573 bc	1573 bc	1306 c	1392 c	1462 bc	1760 ab	1904 a	1465 bc
F53	2815 bc	3288 a	2871 bc	2981 ab	2865 bc	3287 a	2935 ab	2985 ab	2527 c

[1] Fraction size classes 250: 0.250 mm to 2.000 mm; 53: 0.053 mm to 0.250 mm. Treatments followed by the same letter(s) are not different at $P < 0.05$.

the F53 size class, there was a clear indication that the high rate of gliricidia (T2) and the low rate of stylosanthes (T6) had higher values than the other treatments while the lowest value was recorded for the control (T9) treatment. The remaining treatments were not different from each other.

There was more of the F250 size material in the soil the first year after harvest (October 1997) than before the initiation of the experiment in June 1997 (initial) and one year later in October 1998. For the F53, the initial value was greater than the others while the October 1997 value was higher than the ones one year later which were identical regardless of the application of biomass for a second consecutive year (Table 5.5).

Table 5.5. POM size class fractions at different sampling date at N'Tarla, Mali.

Sampling dates	Fraction weight ---------- kg ha^{-1} --------	
	F250	F53
Initial June 1997	1575 b	4375 a
October 1997	1794 a	2609 b
October 1998 R	1385 b	2473 bc
October 1998 B	1365 b	2344 c
P	0.0001	0.0001

Dates followed by the same letter(s) are not significantly different at P = 0.05; R = residual effects; B = biomass applied for a second consecutive year.

Nitrogen Content of Particulate Organic Matter (POM_N)

There were differences among treatments for the soil N content of POM in the first year of the experiment, 1997 (Table 5.1). High rates of biomass application (for gliricidia and stylosanthes), farm-yard manure, and fertilizer treatments had higher N content in 1997. Overall, the ranking was in the order: T2 = T7 > T6 = T8 > T5 = T3 = T4 = T1 > T9. A similar trend was displayed when POM_N values were averaged across sampling dates. There were no differences among the residuals (R) nor among the biomass-applied (B) treatments in 1998.

Similarly, sampling dates had a significant effect on soil POM_N content values as illustrated by Figure 5.2 and Table 5.2. Soil POM_N content was highest in June 1997 before the initiation of the experiment with an average value of 39 kg ha^{-1}. The contrast analysis (Table 5.3) indicated that at harvest in October 1997, the POM_N value was 23% less than its June 1997 value. The lowest POM_N values were recorded one year later with 36% and 38% decrease as compared with the initial value of June 1997, respectively, for the residuals and the biomass-applied treatments. These two groups of treatments were not different from each other.

The analysis of the N content of the different particle size class fractions indicated no difference between the treatments at any particular sampling date except for the F250 fraction at October 1997 after harvest (Table 5.6). At this date and for the F250 fraction, the high rate of gliricidia (T2) and the farm yard manure (T7) applied treatments had the highest N content values. The low rates of gliricidia (T1) and pterocarpus (T4) and the control (T9) treatments yielded the lowest values. The remaining treatments were not different from one another. Overall, the F53 fraction contributed more to the total POM_N than the F250. When the N contents were averaged across years, they displayed significant differences for both fractions (Table 5.7). Here also, the high rate of gliricidia (T2) and the farm-yard manure (T7) treatments had the highest values while T9, T1, and T4 had the lowest ones. In terms of sampling date, the ranking was as follows for both fractions: initial = October 1997 > October 1998 R = October 1998 B.

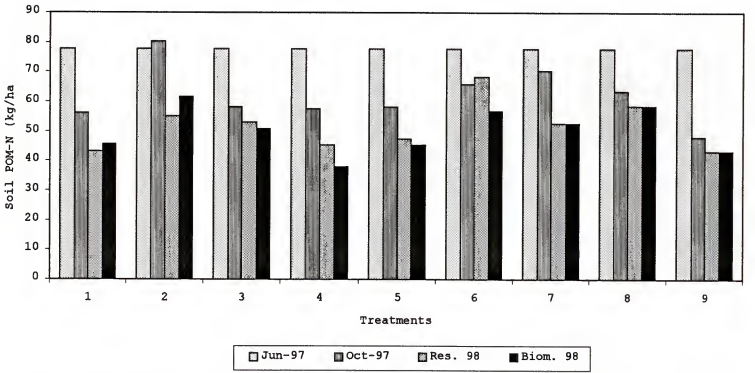

Figure 5.2. N content of POM (0 to 20 cm) at different sampling dates at N'Tarla, Mali. See Table 5.1 for treatment description.

Relationship Between POM Variables and Maize Grain Yield

Correlation analysis between weight and N content of topsoil POM and maize grain yields (Figures 5.3 and 5.4 and Table 5.8) revealed good relationships between total POM weight and total POM N content and maize grain yield in 1997. The coefficient of correlation (r) was higher for POM N content than for POM weight. This relationship was somehow weak in 1998 for both the residuals effects (R) and the biomass-applied (B) treatments. However, the coefficient of correlation was greater with the biomass-applied treatments than with the residual effects. The differences between the initial and the 1997 values of POM and POM_N indicated similar trends. When averaged across years, POM N content displayed a closer relationship with maize grain yield than POM weight (Figures 5.5 and 5.6). The coefficients of determination (R^2) were 0.33 and 0.31 for POM_N and POM weight, respectively. On the contrary, no correlation was found between maize grain yield and the amount of POM and POM-N lost from 1997 to 1998 (results not shown). For the fraction-size classes, F53 had a higher coefficient of determination ($R^2 = 0.54$) than F250 which had a coefficient of only 0.20 (Figure 5.7).

Table 5.6. Nitrogen content of different POM fraction size classes at the N'Tarla research station (Mali) in 1997 and 1998 for residual(R) and biomass applied (B)treatments

Dates	Fraction size[1]	Treatments								
		1	2	3	4	5	6	7	8	9
		kg ha^{-1}								
1997	F250	18.80 c	33.40 a	22.88 bc	19.53 c	21.61 bc	22.58 bc	29.85 ab	22.37 bc	17.93 c
	F53	38.85 a	45.79 a	35.40 a	39.15 a	36.96 a	42.84 a	41.19 a	42.19 a	31.25 a
1998 R	F250	13.56 a	16.00 a	17.91 a	13.62 a	15.85 a	22.55 a	19.02 a	22.39 a	16.42 a
	F53	30.35 a	40.05 a	34.89 a	31.29 a	32.20 a	41.46 a	33.65 a	36.33 a	27.07 a
1998 B	F250	15.65 a	18.97 a	18.01 a	10.98 a	14.07 a	21.37 a	19.02 a	22.39 a	16.42 a
	F53	31.00ab	44.07 a	33.42 ab	27.37 b	31.88 ab	33.05 ab	33.65 ab	36.32 ab	27.07 b
Across time	F250	17.87 c	22.96 a	20.57abc	16.90 c	18.75abc	22.49 ab	22.84 ab	22.65 ab	18.56bc
	F53	38.61bc	46.04 a	39.49 bc	38.01bc	38.82 bc	42.90 ab	40.68abc	42.27 ab	34.91 c

[1] Fraction size classes 250: 0.250 mm to 2.000 mm; 53: 0.053 mm to 0.250 mm Treatments followed by the same letter(s) are not different at $P < 0.05$.

Table 5.7. N content of POM size class fractions at different sampling dates at N'Tarla, Mali.

Sampling dates	Fraction N content ---------- kg ha^{-1} --------	
	F250	F53
Initial June 1997	23.47 a	54.25 a
October 1997	23.22 a	39.29 b
October 1998 R	17.48 b	34.14 c
October 1998 B	17.43 b	33.09 c
P	0.0001	0.0001

Treatments followed by the same letter(s) are not significantly different at P = 0.05; R = residual effects; B = biomass applied for a second consecutive year.

Table 5.8. Correlation coefficients (r) between total soil POM weight and POM N content with maize grain yield at N'Tarla, Mali.

Year	Total POM	Total POM N
1997	0.49**	0.54**
1998 R	0.14	0.22
1998 B	0.25	0.35

Level of signification for r * P < 0.05 and ** P < 0.005.

Table 5.9. Correlation coefficients (r) between weight and N content of different soil POM fraction size classes with maize grain yield at N'Tarla, Mali.

Year	Fractions weight		Fractions N content	
	F250	F53	F250	F53
1997	0.31	0.52**	0.52**	0.46**
1998 R	0.18	0.08	0.18	0.22
1998 B	0.09	0.34	0.19	0.43*

Level of signification for r * P < 0.05 and ** P < 0.005.

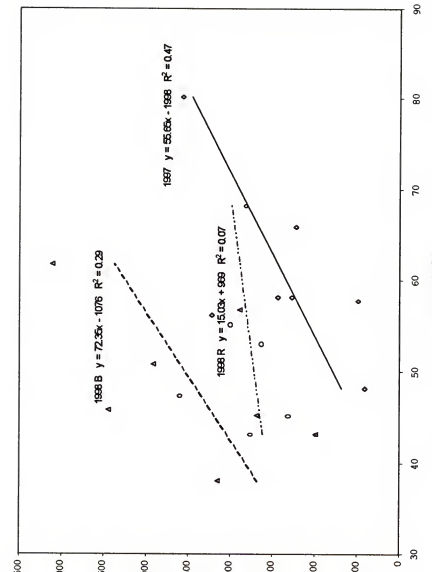

Figure 5.3. Relationship between soil POM N and maize grain yield during two seasons at N'Tarla, Mali.

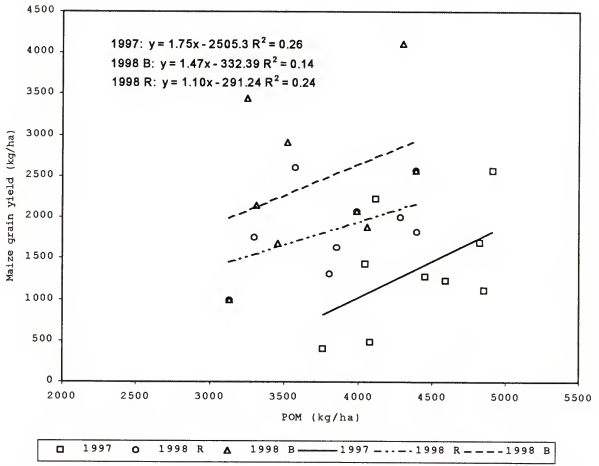

Figure 5.4. Relationship between soil POM and maize grain yield during two seasons at N'Tarla, Mali.

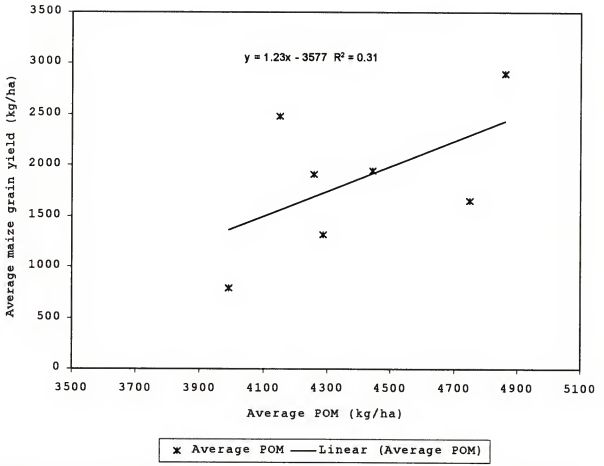

Figure 5.5. Relationship between average soil POM and average maize grain yield during two seasons at N'Tarla, Mali.

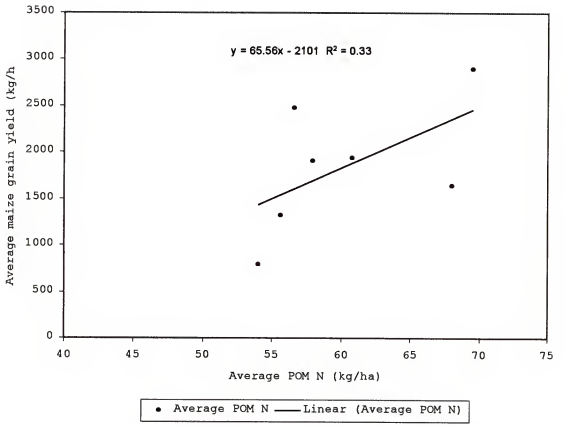

Figure 5.6. Relationship between average soil POM N and average maize grain yield during two seasons at N'Tarla, Mali.

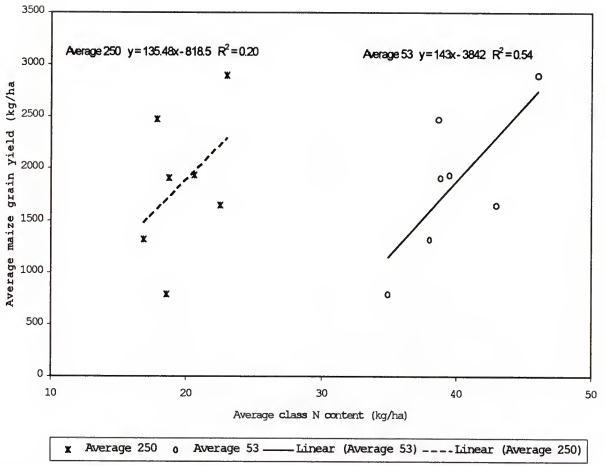

Figure 5.7. Relationship between the average N content of different POM size-fractions and maize grain yield during two seasons at N'Ntarla, Mali.

Discussion

The results consistently revealed a general trend of decline in soil POM weight over time. They corroborate the findings in Chapter 4 which indicated that there was no improvement in soil organic C content during the study period. There was a clear indication that the F53 pool (0.053 to 0.250 mm size fraction) contributed more to total soil POM weight than the larger-size pool, F250 (0.250 to 2.000 mm size fraction). The F53 fraction accounted for nearly 74% of the initial total POM weight and 66% when values were averaged over time. This shows that the soil POM is a dynamic pool in terms of decomposition of added organic materials and mineralization of organic matter. In this pool, large-size fractions serve to nourish small-size fraction pools.

It is well documented that macroorganic matter, i.e., organic matter in the sand-size fraction (>0.053 mm) is generally more labile than organic matter in the finer fractions made up of clay and silt (Tiessen and Stewart, 1983; Gregorich et al., 1988). Soil POM is known to be more influenced by management practices than total soil organic matter (Cambardella and Elliot, 1993; Barrios et al., 1996). Our findings indicated that the biomass-applied treatments had more total POM than the other treatments, and their POM tended to be higher in F53 than in F250

pools. However, the percent decrease in F53 weight is greater than the one for F250. Out of the 25% decrease in total POM weight, only 3% was accounted for by the F250 fraction. Thus, though sample preparation did not allow to assess any undecomposed organic material greater than 2.000 mm in size, it may be correct to assume that large organic fractions undergo more rapid decomposition than small ones.

The results also revealed that POM N content was more closely correlated to maize grain yield than POM total weight. This may well be an indication that the quality of the applied biomass, i.e., its ability to supply nutrients for crop uptake, might be of greater importance than the total weight of organic materials added to the soil. Barrios et al. (1997) reported from an experiment in Zambia that the use of trees with high-quality litter [i.e., low (Lignin + Polyphenols)/N ratio] resulted in higher amounts of N, P, and aerobic N mineralization. The light fraction following trees with high-quality leaf litter had lower C/N, C/P, and N/P ratios. Handayanto et al. (1995) suggested that management of tree fallows for optimum N fixation might be desirable because increased N fixation results in higher N content in leaves and lower polyphenol content in prunings.

Similar to POM weight, there was a general trend of decrease in total soil POM-N content over time. This trend

is supported by the soil analysis results in Chapter 4 which indicated that there was a depletion of total soil N over the study period. Though POM_N represents only a fraction of the total soil N, Vanlauwe et al. (1998) indicated that it contributes more to crop N uptake than N from the other pools, and it may be an important indicator for the soil fertility status of savanna soils. The F53 fraction contributed more to total POM N and was more closely correlated to maize grain yield than the F250. Vanlauwe et al. (1998) reported that the N derived from F250 was released more rapidly than in the other fractions, which might suggest that it would be more readily available for crop uptake. However, our results indicated a higher correlation between maize grain yield and F53 than with F250. This might be an indication that though the two fractions are generally aggregated and termed POM, it would be of interest that future research focuses on F53 as a separate indicator for soil fertility status in the study area.

Conclusion

This fractionation study revealed that the quality of the added materials may be of greater value than their quantity. In that stand point, the POM fraction F53 (0.053

to 0.250 mm size fraction) had higher total weight, higher N content, and was more closely correlated with maize grain yield than the F250 (0.250 to 2.000 mm size fraction). *Gliricidia sepium* and *Stylosanthes hamata* appeared to be more promising than *Pterocarpus erinaceus* as improved fallow species for the region.

Though the length of the study was not long enough to make clear and strong inferences about soil organic matter dynamics, these results suggest that there may be solid ground for future research to examine different POM fractions separately in order to develop appropriate management of organic inputs such as household waste, farmyard manure, crop residues, and MPT prunings.

CHAPTER 6
MODELING CHANGES OF THE FARMING SYSTEMS WITH THE ADOPTION OF IMPROVED FALLOWS USING LINEAR PROGRAMMING (LP)

Introduction

The input of nutrients as fertilizers in the farming systems of the study region is far less than the quantity exported through erosion, leaching, crop harvest, and other natural mechanisms. Lack of cash and adequate infrastructure such as roads, transportation and markets, limit the use of chemical sources of nutrients. Traditionally, farmers have relied on long fallow periods to replenish the soil fertility depleted through cropping. However, due to increases of human and animal populations and land-use pressure, fallows have been reduced both in length and in area or even abandoned in many farming systems.

Short-duration fallows are now being tried as an alternative to the traditional fallows in these farming systems. These improved Fallows are planted to leguminous, fast-growing tree species for shorter periods (3 to 4 years). As noted in Chapters 3, 4, and 5 several studies of

a biophysical nature have ascertained the potentials of such managed fallows to soil fertility replenishment in a number of sub-Saharan countries. However, numerous authors have reported that adoption rates associated with such fallows are low even in places where they are supposed to have greater potential (Hoefsloot et al., 1993; Franzel, 1999; Place and Dewees, 1999; Tarawali et al., 1999). Most of these reports suggest socioeconomic and policy issues as the main reasons for these low adoption rates. It can be hypothesized that (i) low adoption is a result of discrepancies between scientifically sound biophysical findings and political/socioeconomic realities and (ii) providing social and economic information along with the biophysical information related to new technologies can increase adoption rates. The objectives of this research are (i) to assess the potential for adoption of improved fallows by households of different types, (ii) to describe the likely changes in resource allocation and income generation of different types of households with the adoption of an improved fallow in the Koutiala region of southern Mali; and (iii) to analyze the identified changes under different policy scenarios and help policy formulation which may increase the adoption rates of improved fallows in the region.

Materials and Methods

Farming Systems in Southern Mali (Koutiala)

The region is mainly populated with the Minianka, Senoufo, Bobo, and Bamanan ethnic groups. The total population in 1997 was 568,212 inhabitants living in 454 villages (CMDT, 1998). Almost all the population is rural with an annual growth rate of 2%. The population is young, with 44% aged less than 15 and only 3.8% over 65. The working population is 43%.

Farmers have access to local weekly markets to sell products and buy manufactured and other goods. There are no adequate banking facilities and farmers are not very keen on keeping their money in banks. They invest their earnings in cattle which represent a social wealth. Cattle are a key component of the farming systems. They help in nutrient recycling through the production of farm-yard manure. They are also used as a source of power in animal-traction-dominated farm operations and for some social and religious needs, and can be sold to meet some cash requirements for investment. This has resulted in a transfer of livestock ownership from traditional herders to farmers, traders, and urban bureaucrats (World Bank, 1994) and has caused an increase in stocking rate up to 0.3 tropical livestock

units (TLU) ha^{-1}, far beyond the carrying capacity of 0.13 to 0.15 TLU ha^{-1} (Bosma et al., 1993). This situation brought about severe damage to natural resources, pastures in particular.

There is a large variation among farmers according to household composition, land holding, wealth, farm equipment, and their risk-bearing capacities. In the early 1980s, the Sikasso Farming Systems Research team (DRSPR, now ESPGRN), in collaboration with Compagnie Malienne pour le Developpement de Textiles (CMDT, the Malian cotton company), identified four major groups (or recommendation domains) of farmers. This functional/operational classification is summarized as follows (Kleene et al., 1989):

- Type A has at least 15 ha of land, all the required equipment (plow (s), drill(s), cultivator(s), and two pairs of draft oxen), a herd of at least ten cattle, is well trained to properly use the equipment, and is self sufficient in staple food (cereal). This group comprises 26% of the households and 43% of the population in the region (CMDT, 1999).
- Type B has at least 10 ha of land, all the required equipment (plow, drill, cultivator) and one pair of draft oxen, a herd of less than ten cattle, is well trained to properly use the equipment, and is self

sufficient in food. This group represents 48% of the households and 44% of the population in the region (CMDT, 1999).

- Type C has enough land which is poorly managed due to a lack of (or insufficient) agricultural equipment, no more than five cattle and is not self sufficient in food. A farmer in this group could have been in type B but due to special social and/or economic situations lost most of his wealth and is downgraded. In most of the cases he has an adequate technical knowledge and is aware of the economic situation. This group comprises 25% of the households and 8% of the population in the region (CMDT, 1999).
- Type D, unlike the other types, has difficult access to land. The farmers have no training, no cattle and no experience in growing a cash crop. The household can hardly provide food to feed the members for more than five months per year. Type D represents 11% of the households and 5% of the population in the region (CMDT, 1999).

Types A and B, while admittedly the better off farmers of the region, comprise 74% of all farms. They are, therefore, the focus of this study.

The Model

Many sophisticated mathematical analysis tools have been developed to comprehensively analyze household economics and farming systems at multiple scales and serve as decision making tools. Though most of these tools operate on similar basic principles, each of them has specific components and is unique in the way it is handled. For this research, linear programming (LP) is selected to assess the potential adoption of improved fallows by type A and type B households in the Koutiala region. These households are the kind thought most likely to adopt promising new technology.

Linear Programming has three basic components representing (i) the resources in hand, i.e., land, labor, and cash, to be used in combination to undertake (ii) activities, production, consuming, and selling, in an environment under (iii) multiple constraints. The livelihood of a household depends on how well it manages its scarce resources under the many biophysical, social, political, and economic constraints to undertake production activities in conformity with its development objectives. In low-input farming systems, this task has become a skill passed on from one generation to another. Every new undertaking has to be fully checked and analyzed before being adopted and integrated into the prevailing farming

systems. The technologies under consideration here are short duration fallows planted to *Gliricidia sepium* + *Stylosanthes hamata* and *Stylosanthes hamata* alone.

Source and type of data

The data for this research originated primarily from an existing long term data base of the Sikasso Farming Systems Research Team (ESPGRN), from farm surveys conducted in the Koutiala region in 1996 (ESPGRN and Projet Jachère), and at the N'Goukan village during 1997 and 1998 cropping seasons. Data related to crop yield and dry matter production in the research area come mainly from the experiments conducted on farmers' fields at N'Goukan (1996 to 1998) and at the N'Tarla research station in 1997 and 1998. Secondary sources such as other IER programs, CMDT annual reports, and review of literature were used to complement and refine the collected data.

Production activities

Though we are aware of the fact that farmers in this region undertake many activities in their production systems, activities are limited here, for simplicity, to crop (cereals and cash crops) and fodder production. Cotton is solely for sale while the cereals (maize and sorghum)

can be sold and/or used for consumption as staple food. The increasingly important integration of livestock and agriculture in the region and the acute shortages of feed during the six-to-seven-month dry season have made fodder production a necessity for households with cattle. Thus, besides the soil fertility improvement aspects, an improved fallow will directly benefit the system through production of high-quality fodder.

Constraints/limitations

The Malian Cotton Company (CMDT) provides all the required inputs for cotton on loan to the farmers at the beginning of the rainy season. The other crops do not benefit from this pre-financing. Cereal consumption in the region is estimated to be 350 kg person^{-1} year^{-1} with equal preference for maize and sorghum. To reduce weight loss during the dry season, cattle feed should be supplemented by 2 kg of fodder head^{-1} day^{-1} from March to June.

Scenarios

Scenario 1. The farmer pays all expenses for an improved fallow, except for protection against cattle during the dry season. An estimated 825 gliricidia seedlings at 25 CFA/seedling and 10 kg of stylosanthes

seeds at 1000 CFA kg^{-1} are required for one ha of a gliricidia + stylosanthes-improved fallow. The total amount is 30625 CFA ($61.25) ha^{-1}. After meeting the annual fodder requirement of the farm animals, the opportunity to sell fodder is included at an estimated price of 10 CFA kg^{-1} (based on ESPGRN Sikasso figures for a similar or lower-quality fodder made of *Dolichos purpureum* + maize stalks). Dry-matter yield of the improved fallow is 4000, 5000, and 7000 kg ha^{-1} at ages 2, 3, and 4 years, respectively.

Scenario 2. This scenario introduces a 50% subsidy on the installation cost of the improved fallow but, at the same time, reduces by half the monetary value of fodder. Such reduction is in line with the anticipated high adoption of the technology making a higher supply of fodder on the market.

Scenario 3. Total subsidy of the installation cost and no monetary value for fodder. With the anticipation that all type A and B households in the region would adopt the technology, there will be no market for fodder.

Objective Function

Households in these systems have many goals. First among these is food security and this is considered a constraint that must be met. Cash on a seasonal basis for other necessities, as well as food, must also be met as a constraint. While other objectives such as food production or male labor can be maximized, the objective function that has provided best results is to maximize the amount of cash available for discretionary spending at the end of the year after meeting other constraints such as food and cash needs. This is the objective used in the present case.

Results

Validation

The results of the simulation compared with known data are presented in Table 6.1. The Sikasso ESPGRN reports average farm sizes of 15 ha and 10 ha, respectively, for type A and type B households. On average, a type A household allocates 9 ha to cotton, 2 ha to maize, 3.5 ha to sorghum, and variable acreage (ranging from 0.5 to 1 ha) to produce fodder. The results of the simulation were 7.5, 2.03, 3.31, and 0.67 ha, respectively, for cotton, maize, sorghum, and fodder. Type B households allocate 4.36 ha to

cotton, 0.78 ha to maize, 2.30 ha to sorghum and variable acreage to fodder. The simulation resulted in 4.39, 1.27, 2.07, and 0.42 ha, respectively, for cotton, maize, sorghum, and fodder. The households are very dynamic in their evolution and decision making. Thus, these combinations may vary from one year to another depending on the objectives of the household and the resources at its disposal which would result in allocating different acreage. However, based on the 1998 ESPGRN figures, it can be concluded that the model simulates well the situation for both household types in the Koutiala region and can be used to predict whether improved fallow would likely be adopted and changes with the adoption should it occur.

Scenario 1

Tables 6.2 and 6.3 summarize four-year results on land use and end-of-year cash derived from selling activities for type A and B households, respectively. It is interesting to notice that while fodder bank land area was reduced by half after the first year (from 0.67 ha to 0.35 ha) by type A households, there was a slight increase in fodder bank land area by B type households. Type A households would have to reduce maize and sorghum areas to liberate some labor for the installation of an improved

Table 6.1. Allocation of land to different crops by type A and B households (1998 ESPGRN data) in the Koutiala region and comparison with the LP model results.

Crops	LP Simulation		ESPGRN, 1998	
	Type A	Type B	Type A	Type B
Cotton	7.50	4.39	9.07	4.36
Fodder bank	0.67	0.42	0.5 - 1	0.5 - 1
Fertilized maize	2.03	1.27	1.97	0.78
Sorghum	3.31	2.07	3.56	2.30

fallow in year 1. However, these two crops retrieve their initial land area and labor values in subsequent years. To the contrary, the introduction of an improved fallow did not affect the initial allocation of land and labor for the type B households.

The financial situation is presented in Figures 6.1 and 6.2, respectively, for type A and type B households. The redistribution of land and labor undertaken by type A in year 1 resulted in a 5% decrease in the end-of-year cash as compared to the initial/basic plan (Figure 6.1). The family gross income increased by $68, $92 and $223, respectively, in years 2, 3 and 4 for an initial investment of $61.25 for the installation of the improved fallow. The technology is even more lucrative for type B households which did not have to redistribute their resources for the installation of the improved fallow. Their end of year cash

Table 6.2. Activities and end of year cash for type A households in the Koutiala region in scenario 1, and comparison with the basic simulation model.

Activities	Basic	Year 1	Year 2	Year 3	Year 4
Production (ha)					
Cotton	7.50	7.50	7.50	7.50	7.50
Fodder bank	0.67	0.67	0.35	0.35	0.35
Improved fallow	0.00	0.80	0.80	0.80	0.00
Maize after IF	0.00	0.00	0.00	0.00	0.80
Fertilized maize	2.03	1.78	2.03	2.03	1.23
Sorghum	3.31	3.09	3.31	3.31	3.31
Total cultivated land	13.51	13.84	13.99	13.99	13.19
Selling (t)					
Cotton	7.87	7.87	7.87	7.87	7.87
Maize	2.18	1.58	2.18	2.18	2.70
Sorghum	2.07	1.76	2.07	2.07	2.07
Fodder	0.00	0.00	2.26	3.06	4.66
End-of-year cash (USD)	3154.4	3002.8	3222.2	3246.2	3377.4

Table 6.3. Activities and end of year cash for type B households in the Koutiala region in scenario 1, and comparison with the basic simulation model.

Activities	Basic	Year 1	Year 2	Year 3	Year 4
Production (ha)					
Cotton	4.39	4.39	4.39	4.39	4.39
Fodder bank	0.42	0.42	0.53	0.53	0.53
Improved fallow	0.00	0.67	0.67	0.67	0.00
Maize after IF	0.00	0.00	0.00	0.00	0.67
Fertilized maize	1.27	1.27	1.27	1.27	0.60
Sorghum	2.07	2.07	2.07	2.07	2.07
Total cultivated land	8.15	8.82	8.93	8.93	8.26
Selling (t)					
Cotton	3.38	3.38	3.38	3.38	3.38
Maize	0.60	0.60	0.60	0.60	1.37
Sorghum	0.74	0.74	0.74	0.74	0.74
Fodder	0.00	0.00	3.00	3.67	5.00
End-of-year cash (USD)	1653.8	1653.8	1743.8	1763.8	1926.5

increased $90, $110, and $273 compared to the basic plan, respectively, at years 2, 3, and 4 (Figure 6.2).

When the models were given the choice of a gliricidia + stylosanthes and a stylosanthes-planted fallow, the preference was always for stylosanthes under this scenario. Type A households had 0.67 ha of fodder bank, 0.96 ha of gliricidia + stylosanthes, and 1.34 ha of stylosanthes. The fodder bank was dropped out of the rotation after year 1 to make up for the area under cotton. At the end of the fallow period in year 4, the model did not chose to put the stylosanthes-planted fallow into cultivation; rather it included 1.06 ha of fodder bank (Table 6.4). Type B households, on the other hand, had 0.42 ha of fodder bank, 0.67 ha of gliricidia + stylosanthes, and 0.93 ha of stylosanthes. There was a slight increase in the fodder bank area (0.53) in year 2. These proportions were kept throughout the fallow period. At the end of the fallow period in year 4, all the land area under gliricidia + stylosanthes and 65% of the one under stylosanthes was planted to maize in replacement of the fertilized maize (Table 6.5).

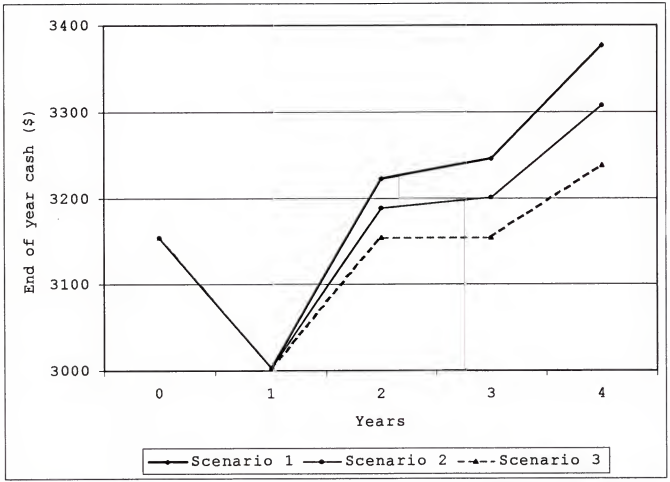

Figure 6.1. Evolution of a Koutiala region type A household end-of-year income under different scenarios.

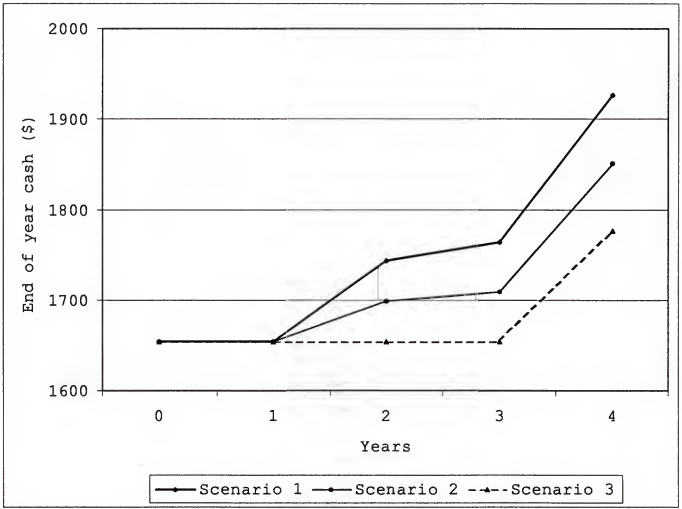

Figure 6.2. Evolution of a Koutiala region type B household end-of-year income under different scenarios.

Scenario 2

Tables 6.6 and 6.7 summarize the results for type A and B households in the Koutiala region. The situation in scenario 2 was identical to the first scenario except that in the latter, the family income was much reduced because of the low monetary value attributed to fodder.

In the situation where farmers had the opportunity to chose between the two types of improved fallows, type B households kept the same allocation of their resources as previously in scenario 1. Type A households had 0.67 ha of fodder bank in year 1 which was dropped out of the rotation in years 2 and 3, 2.3 ha of stylosanthes, and no gliricidia + stylosanthes. However, at the end of the fallow period in year 4, only 42% of the stylosanthes was planted to maize (Tables 6.8 and 6.9).

Scenario 3

For both household types the fodder bank was dropped out of the system after year 1 when the improved fallow started producing fodder for home consumption (Tables 6.10 and 6.11). Family end-of-year cash increased to its initial value with the basic plan ($3154.4) after a 5% decrease in year 1 ($3002.8) and remained constant through year 3 for type A households. Only about a 3% increase ($3237.6) was

Table 6.4. Activities and end-of-year cash for type A households in the Koutiala region in scenario 1 with gliricidia + stylosanthes and stylosanthes improved fallows compared with the basic simulation model.

Activities	Basic	Year1	Year2	Year3	Year4
Production (ha)					
Cotton	7.50	4.80	5.79	5.79	5.79
Fodder bank	0.67	0.67	0.00	0.00	1.06
Improved fallow 1	0.00	0.96	0.96	0.96	0.00
Improved fallow 2	0.00	1.34	1.34	1.34	1.34
Maize after IF 1	0.00	0.00	0.00	0.00	0.96
Maize after IF 2	0.00	0.00	0.00	0.00	0.00
Fertilized maize	2.03	3.81	3.81	3.81	2.85
Sorghum	3.31	3.09	3.09	3.09	2.81
Total cultivated land	13.51	14.67	15.00	15.00	14.82
Selling (t)					
Cotton	7.87	4.99	6.02	6.02	6.02
Maize	2.18	6.36	6.36	6.36	6.99
Sorghum	2.07	0.80	0.80	0.80	0.49
Fodder	0.00	0.00	7.21	10.48	14.63
End-of-year cash (USD)	3154.4	2718.4	3257.8	3355.8	3524.6

Table 6.5. Activities and end of year cash for type B households in the Koutiala region in scenario 1 with gliricidia + stylosanthes and stylosanthes improved fallows compared with the basic simulation model.

Activities	Basic	Year 1	Year2	Year3	Year4
Production (ha)					
Cotton	4.39	4.39	4.39	4.39	4.39
Fodder bank	0.42	0.42	0.53	0.53	0.53
Improved fallow 1	0.00	0.67	0.67	0.67	0.00
Improved fallow 2	0.00	0.93	0.93	0.93	0.33
Maize after IF 1	0.00	0.00	0.00	0.00	0.67
Maize after IF 2	0.00	0.00	0.00	0.00	0.60
Fertilized maize	1.27	1.23	1.27	1.27	0.00
Sorghum	2.07	2.07	2.07	2.07	2.07
Total cultivated land	8.15	9.71	9.86	9.86	8.59
Selling (t)					
Cotton	3.38	3.38	3.38	3.38	3.38
Maize	0.60	0.53	0.60	0.60	1.76
Sorghum	0.74	0.74	0.74	0.74	0.74
Fodder	0.00	0.00	6.73	9.00	9.67
End-of-year cash (USD)	1653.8	1642.6	1855.8	1923.8	2129.4

observed at the end of the fallow period in year 4 (Figure 6.1). Type B households did not suffer any monetary reduction and achieved a 7.5% increase in gross family income at the end of the fallow phase (Figure 6.2).

Tables 6.12 and 6.13 summarize the allocation of resources by farmers in the situation where there were two types of improved fallows and fodder had no monetary value. Type A households did not have a stylosanthes-planted fallow in their rotation. The area under gliricidia + stylosanthes was only 0.11 ha which was all planted to maize in year 4 at the end of the fallow period. The initial 0.67 ha of fodder bank was progressively reduced to become only 0.41 in year 4. On the other hand, type B households had 0.42 ha of fodder bank in year 1, which was eliminated from the rotation from year 2, 0.67 ha of gliricidia + stylosanthes, and 0.82 ha of stylosanthes. All the area under gliricidia + stylosanthes was planted to maize in year 4 while 27 and 73% of the area under stylosanthes was planted to maize in years 3 and 4, respectively.

Table 6.6. Activities and end of year cash for type A households in the Koutiala region in scenario 2, and comparison with the basic simulation model.

Activities	Basic	Year 1	Year 2	Year 3	Year 4
Production (ha)					
Cotton	7.50	7.50	7.50	7.50	7.50
Fodder bank	0.67	0.67	0.35	0.35	0.35
Improved fallow	0.00	0.80	0.80	0.80	0.00
Maize after IF	0.00	0.00	0.00	0.00	0.80
Fertilized maize	2.03	1.78	2.03	2.03	1.23
Sorghum	3.31	3.09	3.31	3.31	3.31
Total cultivated land	13.51	13.84	13.99	13.99	13.19
Selling (t)					
Cotton	7.87	7.87	7.87	7.87	7.87
Maize	2.18	1.58	2.18	2.18	2.70
Sorghum	2.07	1.76	2.07	2.07	2.07
Fodder	0.00	0.00	2.26	3.06	4.66
End-of-year cash (USD)	3154	3002	3188	3200	3307

Table 6.7. Activities and end of year cash for type B households in the Koutiala region in scenario 2, and comparison with the basic simulation model.

Activities	Basic	Year 1	Year 2	Year 3	Year 4
Production (ha)					
Cotton	4.39	4.39	4.39	4.39	4.39
Fodder bank	0.42	0.42	0.53	0.53	0.53
Improved fallow	0.00	0.67	0.67	0.67	0.00
Maize after IF	0.00	0.00	0.00	0.00	0.67
Fertilized maize	1.27	1.27	1.27	1.27	0.60
Sorghum	2.07	2.07	2.07	2.07	2.07
Total cultivated land	8.15	8.82	8.93	8.93	8.26
Selling (t)					
Cotton	3.38	3.38	3.38	3.38	3.38
Maize	0.60	0.60	0.60	0.60	1.37
Sorghum	0.74	0.74	0.74	0.74	0.74
Fodder	0.00	0.00	3.00	3.67	5.00
End-of-year cash (USD)	1653	1653	1698	1708	1851

Table 6.8. Activities and end of year cash for type A households in the Koutiala region in scenario 2 with gliricidia + stylosanthes and stylosanthes improved fallows compared with the basic simulation model.

Activities	Basic	Year 1	Year2	Year3	Year4
Production (ha)					
Cotton	7.50	5.12	5.79	5.79	5.79
Fodder bank	0.67	0.67	0.00	0.00	1.06
Improved fallow 1	0.00	0.00	0.00	0.00	0.00
Improved fallow 2	0.00	2.30	2.30	2.30	1.33
Maize after IF 1	0.00	0.00	0.00	0.00	0.00
Maize after IF 2	0.00	0.00	0.00	0.00	0.97
Fertilized maize	2.03	3.81	3.81	3.81	2.84
Sorghum	3.31	3.09	3.09	3.09	3.00
Total cultivated land	13.51	14.99	14.99	14.99	14.99
Selling (t)					
Cotton	7.87	5.32	6.02	6.02	6.02
Maize	2.18	6.36	6.36	6.36	6.51
Sorghum	2.07	0.80	0.80	0.80	0.70
Fodder	0.00	0.00	7.21	9.52	12.70
End-of-year cash (USD)	3154.4	2823.4	3149.6	3184.2	3237.3

Table 6.9. Activities and end of year cash for type B households in the Koutiala region in scenario 2 with gliricidia + stylosanthes and stylosanthes improved fallows compared with the basic simulation model.

Activities	Basic	Year 1	Year2	Year3	Year4
Production (ha)					
Cotton	4.39	4.39	4.39	4.39	4.39
Fodder bank	0.42	0.42	0.53	0.53	0.53
Improved fallow 1	0.00	0.67	0.67	0.67	0.00
Improved fallow 2	0.00	0.93	0.93	0.93	0.33
Maize after IF 1	0.00	0.00	0.00	0.00	0.67
Maize after IF 2	0.00	0.00	0.00	0.00	0.60
Fertilized maize	1.27	1.23	1.27	1.27	0.00
Sorghum	2.07	2.07	2.07	2.07	2.07
Total cultivated land	8.15	9.71	9.86	9.86	8.59
Selling (t)					
Cotton	3.38	3.38	3.38	3.38	3.38
Maize	0.60	0.53	0.60	0.60	1.76
Sorghum	0.74	0.74	0.74	0.74	0.74
Fodder	0.00	0.00	6.73	9.00	9.67
End-of-year cash (USD)	1653.8	1642.6	1754.8	1788.8	1984.4

Table 6.10. Activities and end of year cash for type A households in the Koutiala region in scenario 3, and comparison with the basic simulation model.

Activities	Basic	Year 1	Year 2	Year 3	Year 4
Production (ha)					
Cotton	7.50	7.50	7.50	7.50	7.50
Fodder bank	0.67	0.67	0.00	0.00	0.00
Improved fallow	0.00	0.80	0.80	0.80	0.00
Maize after IF	0.00	0.00	0.00	0.00	0.80
Fertilized maize	2.03	1.78	2.03	2.03	1.23
Sorghum	3.31	3.09	3.31	3.31	3.31
Total cultivated land	13.51	13.84	13.64	13.64	12.84
Selling (t)					
Cotton	7.87	7.87	7.87	7.87	7.87
Maize	2.18	1.58	2.18	2.18	2.70
Sorghum	2.07	1.76	2.07	2.07	2.07
Fodder	0.00	0.00	0.00	0.00	0.00
End-of-year cash (USD)	3154.4	3002.4	3154.4	3154.4	3237.6

Table 6.11. Activities and end of year cash for type B households in the Koutiala region in scenario 3, and comparison with the basic simulation model.

Activities	Basic	Year 1	Year 2	Year 3	Year 4
Production (ha)					
Cotton	4.39	4.39	4.39	4.39	4.39
Fodder bank	0.42	0.42	0.00	0.00	0.00
Improved fallow	0.00	0.67	0.67	0.67	0.00
Maize after IF	0.00	0.00	0.00	0.00	0.67
Fertilized maize	1.27	1.27	1.27	1.27	0.60
Sorghum	2.07	2.07	2.07	2.07	2.07
Total cultivated land	8.15	8.82	8.40	8.40	7.73
Selling (t)					
Cotton	3.38	3.38	3.38	3.38	3.38
Maize	0.60	0.60	0.60	0.60	1.37
Sorghum	0.74	0.74	0.74	0.74	0.74
Fodder	0.00	0.00	0.00	0.00	0.00
End-of-year cash (USD)	1653.8	1653.8	1653.8	1653.8	1776.5

Table 6.12. Activities and end of year cash for type A households in the Koutiala region in scenario 3 with gliricidia + stylosanthes and stylosanthes improved fallows compared with the basic simulation model.

Activities	Basic	Year 1	Year2	Year3	Year4
Production (ha)					
Cotton	7.50	5.79	5.79	5.79	5.79
Fodder bank	0.67	0.67	0.52	0.45	0.41
Improved fallow 1	0.00	0.11	0.11	0.11	0.00
Improved fallow 2	0.00	0.00	0.00	0.00	0.00
Maize after IF 1	0.00	0.00	0.00	0.00	0.11
Maize after IF 2	0.00	0.00	0.00	0.00	0.00
Fertilized maize	2.03	2.60	3.81	3.81	3.71
Sorghum	3.31	3.09	3.09	3.09	3.09
Total cultivated land	13.51	12.26	13.32	13.25	13.11
Selling (t)					
Cotton	7.87	6.02	6.02	6.02	6.02
Maize	2.18	6.36	6.36	6.36	6.44
Sorghum	2.07	0.80	0.80	0.80	0.80
Fodder	0.00	0.00	0.00	0.00	0.00
End-of-year cash (USD)	3154.4	3041.4	3041.4	3041.4	3052.7

Table 6.13. Activities and end of year cash for type B households in the Koutiala region in scenario 3 with gliricidia + stylosanthes and stylosanthes improved fallows compared with the basic simulation model.

Activities	Basic	Year 1	Year2	Year3	Year4
Production (ha)					
Cotton	4.39	4.39	4.39	4.39	4.39
Fodder bank	0.42	0.42	0.00	0.00	0.00
Improved fallow 1	0.00	0.67	0.67	0.67	0.00
Improved fallow 2	0.00	0.82	0.82	0.60	0.00
Maize after IF 1	0.00	0.00	0.00	0.00	0.67
Maize after IF 2	0.00	0.00	0.00	0.22	0.60
Fertilized maize	1.27	1.27	1.27	1.05	0.00
Sorghum	2.07	2.07	2.07	2.07	2.07
Total cultivated land	8.15	9.64	9.22	9.00	7.73
Selling (t)					
Cotton	3.38	3.38	3.38	3.38	3.38
Maize	0.60	0.60	0.60	0.64	1.76
Sorghum	0.74	0.74	0.74	0.74	0.74
Fodder	0.00	0.00	0.00	0.00	0.00
End-of-year cash (USD)	1653.8	1653.8	1653.8	1659.1	1839.4

Discussion

In the simulation the model underestimated the 1998 area under cotton in Type A households by 17.31% (9.07 ha vs 7.50 ha). However, the prediction was very good when compared with a longer term average (7.36 ha vs 7.50 ha). The other results of the simulation were in the range of acceptability for both household types. The minor deviations observed are an indication of the very nature and the dynamism of these households.

The model indicated that the introduction of *Gliricidia sepium* + *Stylosanthes hamata* and *Stylosanthes hamata*- improved fallows would be attractive to type A and B households in the Koutiala region under both scenarios. The most direct soil fertility benefit to farmers is the increase in crop yield. The average maize grain yield in the region is 2350 kg ha^{-1} and 1870 kg ha^{-1} respectively for type A and B households (ESPGRN, 1998). An improved fallow would be of interest only if it can increase maize grain yield to 3,000 kg ha^{-1}. The results from the on-farm experiment indicated that gliricidia + stylosanthes-planted treatments can achieve similar yields as a result of soil improvement (Chapter 3). Allowing for less than ideal conditions (climate, soil, protection, etc.), this increase would be achieved after four years of fallowing.

Under scenarios 1 and 2, this type of improved fallow represents an interesting venture for types A and B households of the region mostly because of the additional value-product, i.e., fodder, that it provides. Acute fodder shortages during the 6- to 7-month dry season constitute a serious constraint to livestock productivity in this region where integration of crops and animals is the basis of the farming systems (Breman and Traoré, 1987; Kleene et al., 1989; Leloup and Traoré, 1989; Bosma et al., 1996). The model allowed farmers to sell any extra fodder after having satisfied the family consumption requirements of 2,000 kg and 1,260 kg dry matter respectively for type A and type B households. Under these circumstances, type A and type B households produced respectively 10,000 kg and 11,670 kg of extra high-quality fodder for sale from year 2 to year 4 of the fallow phase.

It is interesting to point out that our results indicated farmer preference for improved fallows planted to stylosanthes over the ones planted to gliricidia + stylosanthes in scenarios where fodder was valued at market price. This could be explained by the ease in installation and management of this type of improved fallow both in terms of initial labor and cash investments. Also farmers in the region had experience with planting stylosanthes about ten years ago through previous programs, though at a

very small scale due to seed unavailability and protection constraints. The worsened fodder shortages they have been experiencing for the last decades constitute a real motivation for the technology as evidenced by the number of farmers asking for stylosanthes seeds.

The fact that stylosanthes-planted fallows remain uncultivated even after the fallow period could be an indication that farmers might be more interested in fodder value than the soil fertility aspects of stylosanthes. However, when both soil fertility replenishment translated in terms of increased maize grain yield and fodder production were considered, the farmers' choice shifted toward gliricidia + stylosanthes-planted fallows.

Though selling fodder is not a widespread practice in the region because of its scarcity, not because of lack of market, this option offers a possibility for farmers to diversify their income sources. The most likely use of such high-quality fodder would be to fatten cattle for meat production. The beef market is very healthy in Mali and in the sub-region, especially Cote d'Ivoire where most of such animals are exported to and sold at interestingly high prices. Another activity which is gaining growing interest in the region is the production of dairy products, milk, through well organized farmer cooperatives as a means of diversifying their sources of revenue. Thus, these two

ventures would be even more financially attractive to farmers in the region than selling the fodder. Such alternatives, though not overlooked, were not investigated in the present research because of lack of logistics and time.

Unlike the two previous ones, scenario 3, despite the fact that installation costs were entirely subsidized, appeared to be not financially attractive to farmers in the region. While type B households doubled the value of their initial investment at year 4 with a 3,000 kg ha^{-1} grain yield type A households gained only 35.5% more on their initial investment.

The model revealed interesting differences between the two types of households in the region. Though both household types have serious labor constraints, especially during weeding periods, type B are more constrained when it comes to fallow installation and management. Thus, for type B, labor is more constraining than availability of land. Nevertheless, the model indicated that type B households would benefit more from the value-added of fodder than type A would.

Conclusion

The gliricidia + stylosanthes improved fallow would be an interesting venture for types A and B households in the Koutiala region only if fodder is valued and if maize yields of at least equal to or higher than the regional average yield of 2,500 kg ha^{-1} can be achieved. If improved fodder production is the only objective to achieve through planted fallows, then farmers in the region would prefer stylosanthes which is easier and cheaper to install and manage than gliricidia + stylosanthes-planted fallows. Improved fallows are not financially attractive to farmers if they do not produce benefits other than improved grain yields. Any subsidy program that would prevent farmers from cutting the fodder as secondary output before the end of the planned fallow length would not have adoption potentials.

Detailed studies would be needed in the future to comprehensively evaluate the impact of improved fallow-produced fodder on animal weight gain, milk production, and on the resulting household economy. Similarly the environmental impact of improved fallows should be assessed and valued to better quantify their ecological benefits. Finally, a special fallow installation loan program, similar to the one that cotton enjoys, is worth putting in

place to increase adoption rates of the technology in the region.

CHAPTER 7
SYNTHESIS AND GENERAL CONCLUSIONS

Summary and Conclusion

The main purpose of this research was to assess the general contribution of agroforestry species to soil fertility replenishment through short-term planted/improved fallows in the Koutiala region of southern Mali. To shed light on the subject, supporting results from on-farm and on-station experiments conducted in the region were integrated. The results were examined from both biophysical (Chapters 3, 4, and 5) and socioeconomic (Chapter 6) perspectives, backed up with a thorough review of the current scientific knowledge in the field of soil fertility replenishment in sub-Saharan Africa (Chapter 2).

In Chapter 3, soil properties and maize production were assessed through *Gliricidia sepium* (Jacq.) Walp. (gliricidia), *Pterocarpus erinaceus* Poir. (pterocarpus) and *Stylosanthes hamata* (L) Taub. (stylosanthes) planted fallows in an on-farm trial at N'goukan in the southern Mali region Koutiala. The specific objective of this three-year study was to identify the most suitable woody and

herbaceous species for an agroforestry system and to determine how they contribute, solely and in association, to soil fertility improvement through short-term improved fallows.

This experiment showed that none of the species, taken alone, is a perfect candidate for soil fertility replenishment through improved fallows in the study area. However, each of them has one or more desirable characteristics as a fallow-improving species. While *G. sepium* has high growth rates, good-quality biomass, and is relatively deep rooted, it requires additional labor for weeding during the first two to three years of establishment. *P. erinaceus*, though well adapted, deep rooted, and competition tolerant, is slow growing and may not produce enough biomass in the time horizon of 3 to 4 years of improved fallows in the conditions of Koutiala. *Stylosanthes hamata*, proven to be well adapted to the local conditions, and drought- and weed-tolerant, may be constrained by its shallow rooting depth in soil nitrate uptake. Thus, the best opportunity resides in a combination of species.

The combination gliricidia + stylosanthes has great potentials as short-duration fallow if the standing stylosanthes biomass is cut at the end of the rainy season,

to allow gliricidia to achieve a competition-free growth during the dry season. This is in conformity with the farmers' objective of supplying quality-fodder to cattle during the dry season. However, more research is needed to determine the "optimal quantity" to be cut to prevent nutrient transfer from the fallow to other sites and to assess the profitability of the system in terms of investment in management and labor. If the fallow length is more than seven years, the combination pterocarpus + stylosanthes could be the best option both in terms of investment in labor, management, and soil fertility replenishment. In any case, a two-year fallow duration is unlikely to bring about any significant change in soil fertility status.

Soil properties and maize (*Zea mays*) production as affected by the transfer of different quality biomass was the focus of the two-year experiment conducted at the N'Tarla research station located 45 km southeast of Koutiala (Chapter 4). The hypothesis tested was that the incorporation of tree biomass from outside to the crop fields would improve soil fertility at least to the same extent as when multipurpose trees are grown and their biomass incorporated *in situ*. The objectives were to understand the decomposition and nutrient release patterns

of the same tree species used in the N'Goukan on-farm experiment (Chapter 3) in the conditions of the Koutiala region and to assess the effectiveness of the incorporation of "imported" high quality biomass compared to its *in situ* application on the improvement of soil fertility and maize crop production.

The results have indicated that gliricidia biomass is the fastest decomposing material followed by stylosanthes and pterocarpus. The high lignin concentration of pterocarpus may have played a significant role in its relatively slow decomposition rate.

The application of biomass resulted in satisfactory crop grain yields in both the on-farm and the on-station experiments. Gliricidia + Stylosanthes treatments in on-farm trials (N'Goukan) and sole Gliricidia and stylosanthes treatments in the on-station experiment (N'Tarla research station) yielded more than the region's 1998 average maize grain yield of 2020 kg ha^{-1}. However, considering the short-term nature of the experiments, the results were not conclusive in detecting soil changes.

In Chapter 5, we examined soil organic matter dynamics after addition of different quality biomass. The objectives for this study were to assess the dynamic of the evolution in the soil medium of different quality organic materials

in the Koutiala region, to determine the contribution of different size-fractions to crop yield, and to select species most appropriate for crop nutrition and soil fertility replenishment.

The results revealed that the quality of the added materials may be of greater value than their quantity. The POM fraction of 0.053 to 0.250 mm (F53) had higher total weight, higher N content, and was more closely correlated with maize grain yield than the F250 (0.250 to 2.000 mm).

Socioeconomic and policy issues were the focus of Chapter 6. It was hypothesized that low adoption was a result of discrepancies between scientifically sound biophysical findings and political/socioeconomic realities caused by the traditional sectorial approach and that providing social and economic information along with the biophysical information related to new technologies would increase adoption rates. These hypothesis were tested under three scenarios ranging from full payment of expenses by farmers to total subsidy of the installation costs of a gliricidia + stylosanthes-planted improved fallow with decreasing monetary value for fodder.

The results indicated that the gliricidia + stylosanthes improved fallow would be an attractive venture for equipped households which have cattle and access to land in the Koutiala region, i.e., types A and B, only if

fodder is valued and if maize yields of at least equal to or higher than the regional average yield could be achieved. Improved fallows would not be financially attractive to farmers if they did not produce benefits other than improved grain yields. Any subsidy program which would prevent farmers from cutting the fodder, as secondary output before the end of the planned fallow length, would not have adoption potential.

Future Research

The results from the on-farm experiment indicated that a more reasonable fallow length needs to be worked out by further research. Researcher-managed improved fallows allowing longer fallow phases of 3 to 4 years in duration are highly recommended as follow-up studies. Because fodder is scarce in the region during the dry season and it seriously constrains animal production, which is a strong component of the region's farming systems, such research may be coupled with the investigation on a "optimal quantity of biomass" to be harvested from these fallows and fed to cattle before the end of the fallow period without jeopardizing the soil fertility objective. Likewise, the fate of biomass-derived soil N (using ^{15}N) is recommended to be investigated in the region. Although the length of the

study was not long enough to make clear and strong inferences about soil organic matter dynamics, the results suggest a solid topic for future research, i.e., to examine different POM fractions separately in order to develop appropriate management of organic inputs such as household waste, farm yard manure, crop residues, and MPT prunings. The socioeconomic results of this study pointed out that detailed studies would be needed in the future to comprehensively evaluate the impact of improved fallow-produced fodder on animal weight gain, milk production, and on the resulting household economy. Similarly the environmental impact of improved fallows should be assessed and valued to better quantify their ecological benefits. Finally, a special fallow installation loan program, similar to the one that cotton enjoys, is worth putting in place to increase adoption rates of the technology in the region.

APPENDIX A: MATRIX OF THE LINEAR PROGRAMING MODEL AT YEAR 1 (SCENARIO 1) FOR TYPE B HOUSEHOLDS IN THE KOUTIALA REGION, MALI

Table A.1. Components of the linear programing model at year 1 (scenario 1) for type A households in the Koutiala region, Mali.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Variables	4.80	0.67	0.96	1.34	0.0	0.0	3.81	0.0	0.0	2.60	6.36	3.09	2.60	0.80
Unit income ($)	324		--- 30 ---		----- 160 -----				30		160			180
Land (ha)	1	1	1	1			1					1		
Cash requirements (CFA)	93		61	30			87					8		
Maize accounting (t)							-2.35			1	1			
Maize consumption (t)										-1				
Sorghum accounting (t)												-1.1	1	1
Sorghum consumption (t)													-1	
Fodder accounting (t)		-3						1	1					
Fodder consumption (t)								-1						
Labor: June - July														
Plough (per. days)	2.5						2.5					2.5		
Plant cotton (days)	1.5													
Plant maize (days)							1.75							
Plant sorghum (days)												1.75		
Labor: July - August														
Weeding 1 cotton (per. days)	16.4													
Weeding 1 maize (per. days)							19.7							
Weeding 1 sorghum (per. days)												22.7		
Fertilizer application (per. days)	1.5		2.5	2.5			1.5					0.5		
Insectic. application (per. days)	5													
Plough fodder bank (days)			9	1										
Plough improved fallow (days)		2.5												
Plant fodder bank (days)														
Plant improved fallow (days)		1												

Notes:
1 = cotton; 2 = fodder bank; 3 = *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 4 = *Stylosanthes hamata* improved fallow; 5 = maize following *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 6 = maize following *Stylosanthes hamata* improved fallow; 7 = fertilizer-applied maize; 8 = transfer fodder; 9 = sell fodder; 10 = transfer maize; 11 = sell maize, 12 = sorghum; 13 = transfer sorghum; 14 = sell sorghum; USD 1 = 500 CFA.

Table A.1 (cont'd). Components of the linear programing model at year 1 (scenario 1) for type A households in the Koutiala region, Mali.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Labor August - September														
Weeding 2 cotton (per. days)	16.4													
Weeding 2 maize (per. days)							19.7							
Weeding 2 sorghum (per. days)													22.7	
Weeding 1 fodder bank (per. days)		5.7												
Weeding 1 IF (per. days)			2.5											
Filling IF (per. days)			3											
Ridging (per. days)	3.54						2.25							
Insecticide application (per. days)	5													
Labor: September - October														
Harvest maize (per. days)							42.2							
Labor: October - November		5												
Harvest fodder bank (per. days)														
Harvest cotton (per. days)	41													
Labor: November - December														
Bird scaring (per. days)													4.2	
Harvest improved fallow (per. days)														
Harvest sorghum (per. days)													43	

Notes:
1 = cotton; 2 = fodder bank; 3 = *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 4 = *Stylosanthes hamata* improved fallow; 5 = maize following *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 6 = maize following *Stylosanthes hamata* improved fallow; 7 = fertilizer-applied maize; 8 = transfer fodder; 9 = sell fodder; 10 = transfer maize; 11 = sell maize, 12 = sorghum; 13 = transfer sorghum; 14 = sell sorghum; USD 1 = 500 CFA.

Table A.1 (cont'd). Components of the linear programing model at year 1 (scenario 1) for type A households in the Koutiala region, Mali.

Activities/resources	Sign	Resource limit	Resource use
Land (ha)	<=	15.00	14.67
Maize consumption (t)	<=	-2.60	-2.60
Sorghum consumption (t)	<=	-2.60	-2.60
Fodder consumption (t)	<=	-2.00	-2.00
Cash requirements ($)	<=	900	900
Labor: June - July			
Plough (per. days)	<=	32	29.25
Plant cotton (days)	<=	12	7.20
Plant maize (days)	<=	8	6.68
Plant sorghum (days)	<=	8	5.41
Labor: July - August			
Weeding 1 cotton (per. days)	<=	95	78.67
Weeding 1 maize (per. days)	<=	75	75
Weeding 1 sorghum (per. days)	<=	70	70
Fertilizer application (per. days)	<=	20	14.46
Insecticide application (per. days)	<=	30	23.99
Plough fodder bank (days)	<=	4	1.67
Plough improved fallow (days)	<=	6	5.76
Plant fodder bank (days)	<=	2	0.67
Plant improved fallow (days)	<=	10	10
Labor August - September			
Weeding 2 cotton (per. days)	<=	95	78.67
Weeding 2 maize (per. days)	<=	75	75
Weeding 2 sorghum (per. days)	<=	70	70
Weeding 1 fodder bank (per. days)	<=	6	3.77
Weeding 1 IF (per. days)	<=	3	2.41
Filling IF (per. days)	<=	10	2.89
Ridging (per. days)	<=	30	25.57
Insecticide application (per. days)	<=	30	23.99
Labor: September - October			
Harvest maize (per. days)	<=	312	160.95
Labor: October - November			
Harvest fodder bank (per. days)	<=	70	3.33
Harvest cotton (per. days)	<=	242	196.68
Labor: November - December			
Bird scaring (per. days)	<=	156	12.91
Harvest improved fallow (per. days)	<=	0	0
Harvest sorghum (per. days)	<=	156	132.83
End-of-year cash (CFA)			**2718.43**

APPENDIX B: MATRIX OF THE LINEAR PROGRAMING MODEL AT YEAR 2 (SCENARIO 1) FOR TYPE B HOUSEHOLDS IN THE KOUTIALA REGION, MALI

Table B.1. Components of the linear programing model at year 2 (scenario 1) for type A households in the Koutiala region, Mali.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Variables	5.79	0.0	0.96	1.34	0.0	0.0	3.81	2	7.21	2.60	6.36	3.09	2.60	0.80
Unit income ($)	324	---	30 ---		-----	160 -----			30		160			180
Land (ha)	1	1	1	1	1	1	1					1		
Cash requirements (CFA)	93		61	30			87					8		
Maize accounting (t)					-1.5	-1.5	-2.35			1	1			
Maize consumption (t)										-1				
Sorghum accounting (t)												-1.1	1	1
Sorghum consumption (t)													-1	
Fodder accounting (t)		-3	-4	-4	-4	-4		1	1					
Fodder consumption (t)								-1						
Labor: June - July														
Plough (per. days)	2.5				2.5	2.5	2.5					2.5		
Plant cotton (days)	1.5													
Plant maize (days)					1.75	1.75	1.75							
Plant sorghum (days)												1.75		
Labor: July - August														
Weeding 1 cotton (per. days)	16.4													
Weeding 1 maize (per. days)					19.7	19.7	19.7							
Weeding 1 sorghum (per. days)												22.7		
Fertilizer application (per. days)	1.5		2.5	2.5			1.5					0.5		
Insectic. application (per. days)	5													
Plough fodder bank (days)			9	1										
Plough improved fallow (days)		2.5												
Plant fodder bank (days)														
Plant improved fallow (days)		1												

Notes:

1 = cotton; 2 = fodder bank; 3 = *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 4 = *Stylosanthes hamata* improved fallow; 5 = maize following *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 6 = maize following *Stylosanthes hamata* improved fallow; 7 = fertilizer-applied maize; 8 = transfer fodder; 9 = sell fodder; 10 = transfer maize; 11 = sell maize, 12 = sorghum; 13 = transfer sorghum; 14 = sell sorghum; USD 1 = 500 CFA.

Table B.1. (cont'd). Components of the linear programing model at year 2 (scenario 1) for type A households in the Koutiala region, Mali.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Labor August - September														
Weeding 2 cotton (per. days)	16.4													
Weeding 2 maize (per. days)					19.7	19.7	19.7							
Weeding 2 sorghum (per. days)													22.7	
Weeding 1 fodder bank (per. days)		5.7												
Weeding 1 IF (per. days)			2.5											
Filling IF (per. days)			3											
Ridging (per. days)	3.54				2.25	2.25	2.25							
Insecticide application (per. days)	5													
Labor: September - October														
Harvest maize (per. days)					42.2	42.2	42.2							
Labor: October - November		5												
Harvest fodder bank (per. days)														
Harvest cotton (per. days)	41													
Labor: November - December														
Bird scaring (per. days)													4.2	
Harvest improved fallow (per. days)														
Harvest sorghum (per. days)													43	

Notes:
1 = cotton; 2 = fodder bank; 3 = *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 4 = *Stylosanthes hamata* improved fallow; 5 = maize following *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 6 = maize following *Stylosanthes hamata* improved fallow; 7 = fertilizer-applied maize; 8 = transfer fodder; 9 = sell fodder; 10 = transfer maize; 11 = sell maize, 12 = sorghum; 13 = transfer sorghum; 14 = sell sorghum; USD 1 = 500 CFA.

Table B.1. (cont'd). Components of the linear programing model at year 2 (scenario 1) for type A households in the Koutiala region, Mali.

Activities/resources	Sign	Resource limit	Resource use
Land (ha)	<=	15.00	15
Maize consumption (t)	<=	-2.60	-2.60
Sorghum consumption (t)	<=	-2.60	-2.60
Fodder consumption (t)	<=	-2.00	-2.00
Cash requirements ($)	<=	900	893
Labor: June - July			
Plough (per. days)	<=	32	31.74
Plant cotton (days)	<=	12	8.69
Plant maize (days)	<=	8	6.68
Plant sorghum (days)	<=	8	5.41
Labor: July - August			
Weeding 1 cotton (per. days)	<=	95	95
Weeding 1 maize (per. days)	<=	75	75
Weeding 1 sorghum (per. days)	<=	70	70
Fertilizer application (per. days)	<=	20	15.96
Insecticide application (per. days)	<=	30	28.96
Plough fodder bank (days)	<=	4	0
Plough improved fallow (days)	<=	6	0
Plant fodder bank (days)	<=	2	0
Plant improved fallow (days)	<=	10	0
Labor August - September			
Weeding 2 cotton (per. days)	<=	95	95
Weeding 2 maize (per. days)	<=	75	75
Weeding 2 sorghum (per. days)	<=	70	70
Weeding 1 fodder bank (per. days)	<=	6	0
Weeding 1 IF (per. days)	<=	3	2.41
Filling IF (per. days)	<=	10	0
Ridging (per. days)	<=	30	29.09
Insecticide application (per. days)	<=	30	28.96
Labor: September - October			
Harvest maize (per. days)	<=	312	160.95
Labor: October - November			
Harvest fodder bank (per. days)	<=	70	0
Harvest cotton (per. days)	<=	242	237.5
Labor: November - December			
Bird scaring (per. days)	<=	100	12.91
Harvest improved fallow (per. days)	<=	56	16.33
Harvest sorghum (per. days)	<=	156	132.83
End-of-year cash (CFA)			**3257.85**

APPENDIX C: MATRIX OF THE LINEAR PROGRAMING MODEL AT YEAR 3 (SCENARIO 1) FOR TYPE B HOUSEHOLDS IN THE KOUTIALA REGION, MALI

Table C.1. Components of the linear programing model at year 3 (scenario 1) for type A households in the Koutiala region, Mali.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Variables	5.79	0.0	0.96	1.34	0.0	0.0	3.81	2	10.5	2.60	6.36	3.09	2.60	0.80
Unit income ($)	324		--- 30 ---		----- 160 -----				30		160			180
Land (ha)	1	1	1	1	1	1	1					1		
Cash requirements (CFA)	93		61	30			87					8		
Maize accounting (t)					-1.5	-1.5	-2.35			1	1			
Maize consumption (t)										-1				
Sorghum accounting (t)												-1.1	1	
Sorghum consumption (t)													-1	
Fodder accounting (t)		-3	-6	-5	-6	-5		1	1					1
Fodder consumption (t)								-1						
Labor: June - July														
Plough (per. days)	2.5				2.5	2.5	2.5					2.5		
Plant cotton (days)	1.5													
Plant maize (days)					1.75	1.75	1.75							
Plant sorghum (days)												1.75		
Labor: July - August														
Weeding 1 cotton (per. days)	16.4													
Weeding 1 maize (per. days)					19.7	19.7	19.7					22.7		
Weeding 1 sorghum (per. days)														
Fertilizer application (per. days)	1.5		2.5	2.5			1.5					0.5		
Insectic. application (per. days)	5													
Plough fodder bank (days)			9	1										
Plough improved fallow (days)		2.5												
Plant fodder bank (days)														
Plant improved fallow (days)		1												

Notes:
1 = cotton; 2 = fodder bank; 3 = *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 4 = *Stylosanthes hamata* improved fallow; 5 = maize following *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 6 = maize following *Stylosanthes hamata* improved fallow; 7 = fertilizer-applied maize; 8 = transfer fodder; 9 = sell fodder; 10 = transfer maize; 11 = sell maize, 12 = sorghum; 13 = transfer sorghum; 14 = sell sorghum; USD 1 = 500 CFA.

Table C.1. (cont'd). Components of the linear programing model at year 3 (scenario 1) for type A households in the Koutiala region, Mali.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Labor August - September														
Weeding 2 cotton (per. days)	16.4													
Weeding 2 maize (per. days)					19.7	19.7	19.7							
Weeding 2 sorghum (per. days)													22.7	
Weeding 1 fodder bank (per. days)		5.7												
Weeding 1 IF (per. days)			2.5											
Filling IF (per. days)			3											
Ridging (per. days)	3.54				2.25	2.25	2.25							
Insecticide application (per. days)	5													
Labor: September - October														
Harvest maize (per. days)					42.2	42.2	42.2							
Labor: October - November		5												
Harvest fodder bank (per. days)														
Harvest cotton (per. days)	41													
Labor: November - December														
Bird scaring (per. days)													4.2	
Harvest improved fallow (per. days)														
Harvest sorghum (per. days)													43	

Notes:
1 = cotton; 2 = fodder bank; 3 = *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 4 = *Stylosanthes hamata* improved fallow; 5 = maize following *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 6 = maize following *Stylosanthes hamata* improved fallow; 7 = fertilizer-applied maize; 8 = transfer fodder; 9 = sell fodder; 10 = transfer maize; 11 = sell maize, 12 = sorghum; 13 = transfer sorghum; 14 = sell sorghum; USD 1 = 500 CFA.

Table C.1. (cont'd). Components of the linear programing model at year 3 (scenario 1) for type A households in the Koutiala region, Mali.

Activities/resources	Sign	Resource limit	Resource use
Land (ha)	<=	15.00	15
Maize consumption (t)	<=	-2.60	-2.60
Sorghum consumption (t)	<=	-2.60	-2.60
Fodder consumption (t)	<=	-2.00	-2.00
Cash requirements ($)	<=	900	893
Labor: June - July			
Plough (per. days)	<=	32	31.74
Plant cotton (days)	<=	12	8.69
Plant maize (days)	<=	8	6.68
Plant sorghum (days)	<=	8	5.41
Labor: July - August			
Weeding 1 cotton (per. days)	<=	95	95
Weeding 1 maize (per. days)	<=	75	75
Weeding 1 sorghum (per. days)	<=	70	70
Fertilizer application (per. days)	<=	20	15.96
Insecticide application (per. days)	<=	30	28.96
Plough fodder bank (days)	<=	4	0
Plough improved fallow (days)	<=	6	0
Plant fodder bank (days)	<=	2	0
Plant improved fallow (days)	<=	10	0
Labor August - September			
Weeding 2 cotton (per. days)	<=	95	95
Weeding 2 maize (per. days)	<=	75	75
Weeding 2 sorghum (per. days)	<=	70	70
Weeding 1 fodder bank (per. days)	<=	6	0
Weeding 1 IF (per. days)	<=	3	2.41
Filling IF (per. days)	<=	10	0
Ridging (per. days)	<=	30	29.09
Insecticide application (per. days)	<=	30	28.96
Labor: September - October			
Harvest maize (per. days)	<=	312	160.95
Labor: October - November			
Harvest fodder bank (per. days)	<=	70	0
Harvest cotton (per. days)	<=	242	237.5
Labor: November - December			
Bird scaring (per. days)	<=	100	12.91
Harvest improved fallow (per. days)	<=	56	16.33
Harvest sorghum (per. days)	<=	156	132.83
End-of-year cash ($)			**3355.81**

APPENDIX D: MATRIX OF THE LINEAR PROGRAMING MODEL AT YEAR 4 (SCENARIO 1) FOR TYPE B HOUSEHOLDS IN THE KOUTIALA REGION, MALI

Table D.1. Components of the linear programing model at year 4 (scenario 1) for type A households in the Koutiala region, Mali.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Variables	5.79	1.06	0.0	1.34	0.96	0.0	2.85	2	14.6	2.60	6.99	2.81	2.60	0.49
Unit income ($)	324		--- 30 ---		----- 160 -----				30		160			180
Land (ha)	1	1	1	1	1	1	1					1		
Cash requirements (CFA)	93		61	30			87					8		
Maize accounting (t)					-1.5	-1.5	-2.35			1	1			
Maize consumption (t)										-1				
Sorghum accounting (t)												-1.1	1	1
Sorghum consumption (t)													-1	
Fodder accounting (t)		-3	-7	-5	-7	-5		1	1					
Fodder consumption (t)								-1						
Labor: June - July														
Plough (per. days)	2.5				2.5	2.5	2.5					2.5		
Plant cotton (days)	1.5													
Plant maize (days)					1.75	1.75	1.75							
Plant sorghum (days)												1.75		
Labor: July - August														
Weeding 1 cotton (per. days)	16.4													
Weeding 1 maize (per. days)					19.7	19.7	19.7							
Weeding 1 sorghum (per. days)												22.7		
Fertilizer application (per. days)	1.5		2.5	2.5			1.5					0.5		
Insectic. application (per. days)	5													
Plough fodder bank (days)			9	1										
Plough improved fallow (days)		2.5												
Plant fodder bank (days)														
Plant improved fallow (days)		1												

Notes:
1 = cotton; 2 = fodder bank; 3 = *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 4 = *Stylosanthes hamata* improved fallow; 5 = maize following *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 6 = maize following *Stylosanthes hamata* improved fallow; 7 = fertilizer-applied maize; 8 = transfer fodder; 9 = sell fodder; 10 = transfer maize; 11 = sell maize, 12 = sorghum; 13 = transfer sorghum; 14 = sell sorghum; USD 1 = 500 CFA.

Table D.1. (cont'd). Components of the linear programing model at year 4 (scenario 1) for type A households in the Koutiala region, Mali.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Labor August - September														
Weeding 2 cotton (per. days)	16.4													
Weeding 2 maize (per. days)					19.7	19.7	19.7							
Weeding 2 sorghum (per. days)													22.7	
Weeding 1 fodder bank (per. days)		5.7												
Weeding 1 IF (per. days)			2.5											
Filling IF (per. days)			3											
Ridging (per. days)	3.54				2.25	2.25	2.25							
Insecticide application (per. days)	5													
Labor: September - October														
Harvest maize (per. days)					42.2	42.2	42.2							
Labor: October - November		5												
Harvest fodder bank (per. days)														
Harvest cotton (per. days)	41													
Labor: November - December														
Bird scaring (per. days)													4.2	
Harvest improved fallow (per. days)														
Harvest sorghum (per. days)													43	

Notes:
1 = cotton; 2 = fodder bank; 3 = *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 4 = *Stylosanthes hamata* improved fallow; 5 = maize following *Gliricidia sepium* + *Stylosanthes hamata* improved fallow; 6 = maize following *Stylosanthes hamata* improved fallow; 7 = fertilizer-applied maize; 8 = transfer fodder; 9 = sell fodder; 10 = transfer maize; 11 = sell maize, 12 = sorghum; 13 = transfer sorghum; 14 = sell sorghum; USD 1 = 500 CFA.

Table D.1. (cont'd). Components of the linear programing model at year 4 (scenario 1) for type A households in the Koutiala region, Mali.

Activities/resources	Sign	Resource limit	Resource use
Land (ha)	<=	15.00	14.82
Maize consumption (t)	<=	-2.60	-2.60
Sorghum consumption (t)	<=	-2.60	-2.60
Fodder consumption (t)	<=	-2.00	-2.00
Cash requirements ($)	<=	900	807.70
Labor: June - July			
Plough (per. days)	<=	32	32
Plant cotton (days)	<=	12	8.69
Plant maize (days)	<=	8	6.68
Plant sorghum (days)	<=	8	4.91
Labor: July - August			
Weeding 1 cotton (per. days)	<=	95	95
Weeding 1 maize (per. days)	<=	75	75
Weeding 1 sorghum (per. days)	<=	70	63.62
Fertilizer application (per. days)	<=	20	14.37
Insecticide application (per. days)	<=	30	28.96
Plough fodder bank (days)	<=	4	2.65
Plough improved fallow (days)	<=	6	1.06
Plant fodder bank (days)	<=	2	0
Plant improved fallow (days)	<=	10	0
Labor August - September			
Weeding 2 cotton (per. days)	<=	95	95
Weeding 2 maize (per. days)	<=	75	75
Weeding 2 sorghum (per. days)	<=	70	63.62
Weeding 1 fodder bank (per. days)	<=	6	6
Weeding 1 IF (per. days)	<=	3	0
Filling IF (per. days)	<=	10	0
Ridging (per. days)	<=	30	29.09
Insecticide application (per. days)	<=	30	28.96
Labor: September - October			
Harvest maize (per. days)	<=	312	160.95
Labor: October - November			
Harvest fodder bank (per. days)	<=	70	5.31
Harvest cotton (per. days)	<=	242	237.5
Labor: November - December			
Bird scaring (per. days)	<=	100	11.74
Harvest improved fallow (per. days)	<=	56	6.71
Harvest sorghum (per. days)	<=	156	120.73
End-of-year cash ($)			**3524.56**

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BIOGRAPHICAL SKETCH

Born in 1957 at Ambiri Habé, Mali, where he completed his elementary schooling, the limited availability of schooling facilities forced Bocary Kaya to move to other places in the country (Niafunké, Tomboctou, and Katibougou) to pursue his education. Kaya graduated from the Institut Polytechnic Rural de Katibougou (I.P.R.), Mali in 1984 with a B.Sc. in agronomy. After serving his military term in 1986 he was assigned to the Sikasso Farming Systems Research Team (DRSPR) to lead a soil conservation program, a position he held until 1995, when he left the country to study for a Ph.D. degree at the University of Florida. Prior to coming to Florida, Kaya earned the degree of Master of Science in Soil Conservation from Silsoe College in the United Kingdom. Bocary is married to Arunya Limbanyen and the couple has a two-and-half-year-old daughter, Aissata.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

P.K.R. Nair, Chairman
Professor of Forest
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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

G. Kidder
Professor of Soil and Water
Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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